AEDC-TR-66-116

eq5

CHARTS OF NORMAL SHOCK WAVE PROPERTIES IN IMPERFECT NITROGEN (SUPPLEMENT: M_S = 1 TO 10)

Clark H. Lewis and E. G. Burgess, III
ARO, Inc.

September 1966

Distribution of this document is unlimited.

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

CHARTS OF NORMAL SHOCK WAVE PROPERTIES IN IMPERFECT NITROGEN (SUPPLEMENT: $M_S = 1$ TO 10)

Clark H. Lewis and E. G. Burgess, III
ARO, Inc.

Distribution of this document is unlimited.

FOREWORD

The results of the calculations presented were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The Program Element was 62405334, Project 8953, Task 895303. The work was conducted under ARO Project No. VW3507, and the manuscript was submitted for publication on May 17, 1966.

The authors are indebted to C. A. Neel, ARO, Inc., for the constant pressure and entropy interpolations, and computation of the speed of sound data from the data of Grabau and Brahinsky, ARO, Inc. The charts were prepared by Thelbert Shields of the von Kármán Gas Dynamics Facility, ARO, Inc., and Virginia Polytechnic Institute, Blacksburg, Virginia.

This technical report has been reviewed and is approved.

Larry R. Walter
Captain, USAF
Analysis Division
Directorate of Plans and Technology

Donald D. Carlson
Colonel, USAF
Director of Plans and Technology

ABSTRACT

Gasdynamic properties which include the effects of dissociation and intermolecular forces (van der Waals) are presented for incident and reflected shock waves in equilibrium imperfect nitrogen. Charts are presented for incident shock Mach numbers in the range from 1 to 10 into (ideal) nitrogen at a temperature of 300°K and pressures in the range from 10^{-4} to 10^{3} cm Hg. The temperature and density in any region do not exceed, respectively, 15,000°K and 1000 amagats. In addition to the usual incident and reflected shock properties, stagnation conditions upstream and downstream and conditions immediately downstream of a standing shock wave are also presented. At pressures above one atmosphere in the undisturbed gas, the effects of the intermolecular forces on the gasdynamic properties are demonstrated.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

a	Speed of sound, ft/sec
h	Enthalpy, ft^2/sec^2
M	Mach number
M_S	Incident shock Mach number, U_S/a_1
p	Pressure, atm
$\dot{q}$	Sphere stagnation heat-transfer rate, Btu/ft^2-sec
R	Gas constant, ft^2/sec^2 °K

r_n	Sphere (nose) radius, in.
S	Entropy, $ft^2/sec^2\ ^\circ K$
T	Temperature, °K
U_R	Reflected shock wave velocity, ft/sec
U_S	Incident shock velocity, ft/sec
u	Gas velocity, ft/sec
W	Molecular weight
Z	Compressibility factor
γ	Ratio of specific heats
ρ	Density, amagats
μ	Viscosity coefficient, dimensionless

SUPERSCRIPTS

(n)	Iteration index
*	Dimensional pressure in lbf/ft^2 and dimensional density in $lbf\text{-}sec^2/ft^4$

SUBSCRIPTS

1	Conditions in the quiescent gas
2	Conditions behind the incident shock
5	Conditions behind the reflected shock
a	Conditions at one atmosphere pressure and 273.15°K
w	Conditions at the wall (300°K)

DOUBLE SUBSCRIPTS

ij	Unless otherwise noted, a ratio, e.g., ρ_i/ρ_j
20	Stagnation conditions upstream of a standing shock wave
20'	Stagnation conditions downstream of a standing shock wave
2s	Conditions downstream of a standing shock wave

USEFUL CONSTANTS

a_a = 1105.55 ft/sec = 0.337006 mm/μsec or km/sec

p_a = 1 atm = 14.696 lbf/in.^{2} = 2116.224 lbf/ft^2 = 1.013236 x 10^6 dynes/cm^2

= 760 mm Hg = 1.013246 x 10^5 newtons/m^2

R = 3196.793 ft^2/sec^2 °K = 1.98717 cal/mole °K = 296.992 m^2/sec^2 °K

= 7.0943286 x 10^{-2} cal/gm °K or Btu/lbm °R

T_a = 273.15 °K = 491.67 °R

W = 28.0134 gm/mole

ρ_a = 2.423516 x 10^{-3} lbf-sec^2/ft^4 or slugs/ft^3 = 7.7974207 x 10^{-2} lbm/ft^3

= 1.2490294 kg/m^3 = 1.2490294 x 10^{-3} gm/cm^3

REFERENCE QUANTITIES

T_1 = 300 °K = 540 °R

a_1 = 1158.729 ft/sec = 0.35318041 mm/μsec or km/sec

h_1 = $\gamma RT_1/(\gamma - 1)$ = 3.3566326 x 10^6 ft^2/sec^2

p_1	
cm Hg	atm
10^3	13.15789
400	5.2631576
200	2.6315788
10^2	1.315789
76	1
10	1.315789^{-1}
1	1.315789^{-2}
10^{-1}	1.315789^{-3}
10^{-2}	1.315789^{-4}
10^{-3}	1.315789^{-5}
10^{-4}	1.315789^{-6}

ρ_1
amagats
11.980259
4.792105
2.3960525
1.1980259
0.9105000
1.1980259^{-1}
1.1980259^{-2}
1.1980259^{-3}
1.1980259^{-4}
1.1980259^{-5}
1.1980259^{-6}

SECTION I
INTRODUCTION

Lack of adequate thermodynamic properties of gases at high pressure and temperatures up to 15,000°K has prompted the AEDC to support work on these properties at the National Bureau of Standards (NBS) for several years (Refs. 1 to 4). Also, the specific heat and speed of sound data at these conditions have been computed by Landis and Nilson (Ref. 5) and Lewis and Neel (Refs. 6 to 8). The more recent NBS data were interpolated at constant entropy and at constant pressure by Neel and Lewis in Refs. 8 to 12 (see also Ref. 13).

The recent data of NBS and VKF noted above were used by Lewis and Burgess to compute normal shock wave properties in imperfect* air (Ref. 14) and nitrogen (Ref. 15) in the range $M_S = 6$ to 30 over the pressure range $p_1 = 10^{-4}$ to 1000 cm Hg (see also Refs. 16 and 17). These imperfect gas results were compared with the perfect gas results of Feldman (Ref. 18) for air and Bernstein for nitrogen (Ref. 19). The comparisons showed non-negligible effects on such quantites as Z, ρ, and a in the stagnation and reflected regions.

The need for data below 1500°K has prompted the VKF to extend the NBS results to lower temperatures (see Refs. 20 and 21). Recently the data for nitrogen have been extended to higher pressures by Grabau and Brahinsky (Ref. 22) using an extrapolation procedure and requiring internal consistency and satisfaction of the laws of thermodynamics.

The recent NBS data (Ref. 3), the low pressure data of Humphrey and Neel (Ref. 20), and some recent unpublished data of Grabau and Brahinsky using the methods described in Ref. 22 were used by Lewis and Burgess (Ref. 23) to compute the normal shock wave properties in imperfect air in the range $M_S = 1$ to 10 and $p_1 = 10^{-4}$ to 1000 cm Hg.

The data in the present report cover the same range of conditions in imperfect nitrogen. The data of Hilsenrath and Klein (Ref. 4), Little

---

*The following terminology will be used in this report. An ideal gas will denote a gas obeying the equations $p = \rho RT$ and $h = C_pT$. A perfect gas will denote one obeying $p = Z\rho RT$ which includes dissociation and ionization neglecting intermolecular effects. An imperfect gas obeys $p = Z\rho RT$ but includes intermolecular forces. The term real gas is reserved for a gas under actual (experimental) conditions and is not subject to the theoretical approximations.

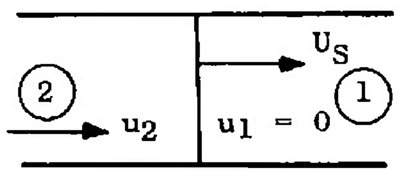
and Neel (Ref. 21), and Grabau and Brahinsky (Ref. 22) were interpolated at constant pressure and entropy, and the specific heat and speed of sound data were computed by Neel and Brahinsky for the single set of data from the above three sources. The present results supplement the earlier calculations of Lewis and Burgess in the range $M_S = 1$ to 6. In the region where the present data overlap the previously published data at lower pressures, the results are identical. However, the data presented herein are plotted to a larger scale than used previously to permit increased accuracy in reading and interpolating the graphical results.

The purpose of the present report is to present the solutions of the normal shock wave equations where the effects of intermolecular forces have been taken into account. The conditions behind the incident and reflected shocks, the stagnation conditions upstream and downstream, and conditions immediately downstream of a standing normal shock wave (see Fig. 1) are presented in graphical form. Charts for pressure, p, temperature, T, velocity, u, enthalpy, h, compressibility factor, Z, entropy, S, and speed of sound, a, in the above-mentioned regions will be given non-dimensionalized by appropriate quantities in the quiescent gas. In addition, M_2 and $(\dot{q}\sqrt{r_n})_{20}'$, are also given.

SECTION II
NORMAL SHOCK EQUATIONS AND CALCULATION PROCEDURE

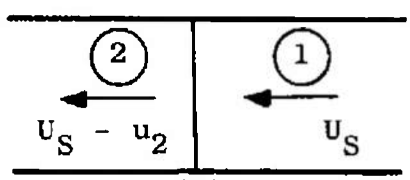
2.1 INCIDENT SHOCK

Consider first a plane shock wave moving into a quiescent gas as shown in the following sketch:



(a)

The shock wave has a velocity U_S with respect to the coordinate system fixed in the quiescent gas. By superposing a velocity $(-U_S)$ on the coordinate system, the shock now is stationary in the new coordinate system as shown below:



(b)

where all other quantities are invariant under the transformation.

The continuity, momentum, and energy equations for the system shown in sketch (b) are

$$\rho_2^* (U_S - u_2) = \rho_1^* U_S \quad (1)$$

$$p_2^* + \rho_2^* (U_S - u_2)^2 = p_1^* + \rho_1^* U_S^2 \quad (2)$$

$$h_2 + \tfrac{1}{2} (U_S - u_2)^2 = h_1 + \tfrac{1}{2} U_S^2 \quad (3)$$

Eliminating u_2 from Eqs. (1) through (3) yields

$$p_2/p_1 = 1 + \rho_1 U_S^2 (1 - \rho_{12})/p_1 RT_a \quad (4)$$

$$h_2/h_1 = 1 + U_S^2 (1 - \rho_{12}^{\ 2})/2h_1 \quad (5)$$

Equations (4), (5), and the equation of state,

$$\rho_2 = \rho(p, h) \quad (6)$$

form the system of equations for the unknowns ρ_2, p_2, and h_2 to be computed with the given shock velocity, U_S, and the conditions in the quiescent gas denoted by subscript 1. Double subscripts denote ratios, e. g., $\rho_{12} = \rho_1/\rho_2$.

The thermodynamic data were interpolated at constant pressure by Neel, and the data were arranged in tables of the form $\phi = \phi\,(\log p; \log \rho, h/RT, S/R, T, Z)$*. The data were interpolated in the range $\log p = -7.4(0.1)4.8$.

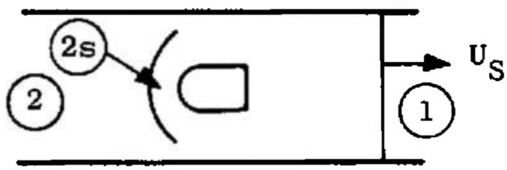
The calculating procedure for the solution of Eqs. (4) through (6) was as follows: With the given conditions and an initial guess for $\rho_{12}\left(\text{say } \rho_{12}^{(0)}\right)$, Eqs. (4) and (5) were solved for p_2 and h_2. The constant pressure interpolated thermodynamic data were used to determine ρ_2 by Eq. (6), and then $\rho_{12}^{(1)}$ was computed. A comparison between $\rho_{12}^{(1)}$ and $\rho_{12}^{(0)}$ was made, and the procedure was repeated until $|\rho_{12}^{(n)} - \rho_{12}^{(n-1)}| < 0.00005$. All properties except the speed of sound, a, were determined from a table-look-up procedure in the constant pressure interpolated data. The speed of sound data were tabulated in the form $a = a\,(S/R;\ \log p,\ \log \rho, h/RT, T, Z)$ and in the range $S/R = 11.6(0.2)50$.

---

*This notation is used to denote $\log p$ and any <u>one</u> of the remaining quantities as independent variables; thus any quantity shown can be determined from the two independent variables.

2.2 STANDING SHOCK

A standing normal shock, such as the bow shock in front of a body, is shown in the following sketch:



where 2s denotes conditions immediately downstream of the standing shock.

The conservation equations are

$$\rho_2^* u_2 = \rho_{2s}^* u_{2s} \tag{7}$$

$$p_2^* + \rho_2^* u_2^2 = p_{2s}^* + \rho_{2s}^* u_{2s}^2 \tag{8}$$

$$h_2 + \tfrac{1}{2} u_2^2 = h_s + \tfrac{1}{2} u_{2s}^2 \tag{9}$$

and eliminating u_{2s} yields

$$p_{2s}/p_2 = 1 + \rho_2 u_2^2 \left[1 - (\rho_2/\rho_{2s})\right]/p_2 RT_a \tag{10}$$

$$h_{2s}/h_2 = 1 + u_2^2 \left[1 - (\rho_2/\rho_{2s})^2\right]/2h_2 \tag{11}$$

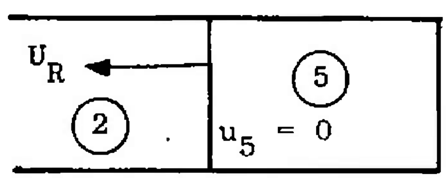
Equations (10) and (11) with the equation of state,

$$\rho_{2s} = \rho(p, h) \tag{12}$$

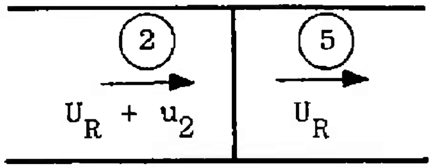
complete the system of equations in the unknowns p_{2s}, h_{2s}, and ρ_{2s}. The method of solution was identical to that used in the incident shock case.

2.3 REFLECTED SHOCK

A normal shock wave reflected from the closed end of a (one-dimensional) tube is shown in the following sketch:



which, when transformed to a coordinate system fixed with respect to the shock wave, becomes



The conservation equations in the transformed coordinate system are

$$\rho_2^* (U_R + u_2) = \rho_5^* U_R \tag{13}$$

$$p_2^* + \rho_2^* (U_R + u_2)^2 = p_5^* + \rho_5^* U_R^2 \tag{14}$$

$$h_2 + \tfrac{1}{2} (U_R + u_2)^2 = h_5 + \tfrac{1}{2} U_R^2 \tag{15}$$

and eliminating u_2 results in

$$p_5/p_2 = 1 + \rho_2 U_R^2 (1 - \rho_{25})/p_2 \rho_{25}^2 RT_a \tag{16}$$

$$h_5/h_2 = 1 + p_2 (p_{52} - 1)(1 + \rho_{25}) RT_a/2\rho_2 h_2 \tag{17}$$

with the equation of state in the form

$$\rho_5 = \rho(p, h) \tag{18}$$

Using Eqs. (1) and (13) to eliminate u_2 gives an expression for U_R in terms of U_S, ρ_{12}, and ρ_{25} as follows:

$$U_R = U_S (1 - \rho_{12}) \rho_{25}/(1 - \rho_{25}) \tag{19}$$

Equations (16) through (19) were solved in a similar manner to the incident shock case.

2.4 STAGNATION CONDITIONS

The isentropic stagnation conditions upstream and downstream of a standing shock wave were determined, respectively, from table-look-up procedures of the form $\phi = \phi(S_2, h_0)$ and $\psi = \psi(S_{2s}, h_0)$ where ϕ and ψ represent all thermodynamic quantities and $h_0 = h_2 + \tfrac{1}{2} u_2^2$.

SECTION III
RESULTS AND DISCUSSION

The results of the calculations are presented in Figs. 2 through 6.* The ideal gas ($\gamma = 1.4$) results are also shown for comparison. Figure 2

*The tabulated numerical results can be obtained from the first author upon written request.

shows the pressure, density, temperature, enthalpy, velocity, speed of sound, Mach number, compressibility factor, and entropy behind the incident shock wave. Similar data for the conditions downstream of the standing shock, stagnation conditions upstream of the shock, and conditions behind the reflected shock are given in Figs. 3 through 6.

The sphere stagnation heat-transfer rate $(\dot{q}\sqrt{r_n})_{20'}$ was computed by the Fay and Riddell (Ref. 24) formula similar to the form used previously by Lewis and Burgess (Refs. 25 and 26)

$$\dot{q}\sqrt{r_n} = 7.55274 \times 10^{-3} (\rho_w \mu_w)^{0.1} (\rho_{20'} \mu_{20'})^{0.4} (h_o - h_w) \left[(p_{20'}/\rho_{20'}) (1 - p_2/p_{20'})\right]^{0.25}$$

with dimensions Btu $\sqrt{\text{in.}}/\text{ft}^2$-sec. The viscosity data were those of Ahtye and Peng (Ref. 27).

Where the thermodynamic properties could be interpolated from the data of Hilsenrath and Klein (Ref. 4), and the data of Grabau and Brahinsky (Ref. 22), conditions were computed for incident shocks in the range $M_S = 1\,(0.5)\,10$ and quiescent gas pressures in the range $p_1 = 1.32 \times 10^{-6}$ to 13.16 atm.

The quantities most affected by the intermolecular forces are Z, ρ, and a. The effects on Z above one atmosphere in region 2 can be seen, for example, from Fig. 2h. The effect on ρ was demonstrated earlier by Lewis and Burgess (Ref. 15) and Lewis (Ref. 17) by comparison of their results with the perfect gas results of Bernstein (Ref. 19) and Ahtye and Peng (Ref. 27). The effect on a was also demonstrated by Lewis and Neel (Ref. 13) by similar comparisons with the perfect gas speed of sound data of Ahtye and Peng (Ref. 27).

Comparisons were previously made by Lewis and Burgess (Ref. 15) between their results and those of Bernstein (Ref. 19) at p_1 up to 200 cm Hg. Below one atmosphere, the differences were well within plotting accuracy, i.e., less than one percent. At 2.6 atmospheres in the quiescent gas, the differences in Z_5, ρ_5, and U_R were as much as 10 percent at $M_S = 12$. The influence of the intermolecular forces was, of course, largest at the highest densities. Lack of perfect gas results at higher pressures prevented further comparisons, and similarly, lack of perfect gas speed of sound data and results in the 20 region prevented further comparisons.

The results presented herein at $p_1 = 1000$ cm Hg were almost entirely based on the data of Grabau and Brahinsky (Ref. 22), which were obtained by extrapolating published thermodynamic data to 1000 amagats and by demanding internal consistency and satisfaction of the laws of

thermodynamics. However, the data are subject to approximate numerical treatment, and thus the results contained herein reflect the inaccuracies caused by numerically fitting, extrapolating, interpolating, and differentiating the basic thermodynamic data.

The effects of joining the extrapolated data of Grabau and Brahinsky with the previous data of Hilsenrath and Klein (Ref. 4) can be seen in Fig. 5f. The curves at 200 and 100 cm Hg below $M_S = 7.5$ were calculated based on the extrapolated data of Grabau and Brahinsky, whereas above $M_S = 7.5$ the data are those of Hilsenrath and Klein. The differences where the data sources join are small, and the trends of the results are as expected. Since Hilsenrath and Klein included only two virial coefficients, whereas the extrapolation of Grabau and Brahinsky was not based on a virial equation of state, the extrapolated Z must be equal to or greater than the one including only the second virial correction. Small deviations are thus to be expected in the present results, but it is hoped that the results are little affected by the numerical procedures.

Finally, comparison of the results in this report with those in air (Ref. 23) for the same initial conditions would indicate the effects of oxygen vibration and dissociation on the gasdynamic properties behind incident and reflected shock waves. The effects are larger at the lower p_1 where the effects of oxygen dissociation can easily be seen from Ref. 23 for quantities such as ρ, T, and a in the stagnation and reflected regions. It is thus hoped that the present charts will be useful to those interested in low as well as high initial pressure experimental and theoretical studies in nitrogen.

SECTION IV
CONCLUDING REMARKS

Normal shock wave parameters have been calculated using imperfect gas thermodynamic properties. The results well below one atmosphere pressure in the quiescent gas are in agreement with the previous calculations using perfect gas properties. At one atmosphere and above, the effects of the intermolecular forces on the imperfect gas properties and hence on the normal shock parameters were previously demonstrated (see Ref. 15). Moreover, as p_1 increases imperfect gas effects increase.

REFERENCES

1. Hilsenrath, J. and Beckett, C. W. "Tables of Thermodynamic Properties of Argon-Free Air to 15,000°K." AEDC-TN-56-12 (AD98974), September 1956.

2. Hilsenrath, J., Klein, M., and Woolley, H. W. "Tables of Thermodynamic Properties of Air Including Dissociation and Ionization from 1500°K to 15,000°K." AEDC-TR-59-20 (AD229962), December 1959.

3. Hilsenrath, J. and Klein, M. "Tables of Thermodynamic Properties of Air in Chemical Equilibrium Including Second Virial Corrections from 1500°K to 15,000°K." AEDC-TDR-63-161 (AD416040), August 1963. Also AEDC-TR-65-58 (AD612301), March 1965.

4. Hilsenrath, J. and Klein, M. "Tables of Thermodynamic Properties of Nitrogen in Chemical Equilibrium Including Second Virial Corrections from 2000°K to 15,000°K." AEDC-TDR-63-162 (AD432210), March 1964. Also AEDC-TR-66-65 (AD630431), April 1966.

5. Landis, F. and Nilson, E. N. "Thermodynamic Properties of Ionized and Dissociated Air from 1500 to 15,000°K." Pratt and Whitney Aircraft Company Report 1921, January 1961.

6. Lewis, C. H. and Neel, C. A. "Specific Heat and Speed of Sound Data for Imperfect Air." AEDC-TDR-64-36 (AD600469), May 1964.

7. Lewis, C. H. and Neel, C. A. "Specific Heat and Speed of Sound Data for Imperfect Nitrogen I. T = 100 to 2200°K." AEDC-TDR-64-113 (AD601241), June 1964.

8. Lewis, C. H. and Neel, C. A. "Specific Heat and Speed of Sound Data for Imperfect Nitrogen II. T = 100 to 2200°K." AEDC-TDR-64-114 (AD601205), June 1964.

9. Neel, C. A. and Lewis, C. H. "Interpolations of Imperfect Air Thermodynamic Data I. At Constant Entropy." AEDC-TDR-64-183 (AD605471), September 1964.

10. Neel, C. A. and Lewis, C. H. "Interpolations of Imperfect Air Thermodynamic Data II. At Constant Pressure." AEDC-TDR-64-184 (AD446386), September 1964.

11. Neel, C. A. and Lewis, C. H. "Interpolations of Imperfect Nitrogen Thermodynamic Data I. At Constant Entropy." AEDC-TDR-64-212 (AD449409), October 1964.

12. Neel, C. A. and Lewis, C. H. "Interpolations of Imperfect Nitrogen Thermodynamic Data II. At Constant Pressure." AEDC-TDR-64-213 (AD449381), October 1964.

13. Lewis, C. H. and Neel, C. A. "Thermodynamic Properties for Imperfect Air and Nitrogen to 15,000°K." AIAA J., Vol. 2, No. 10, October 1964, pp. 1847-1849.

14. Lewis, C. H. and Burgess, E. G., III. "Charts of Normal Shock Wave Properties in Imperfect Air." AEDC-TDR-64-43 (AD433958), March 1964.

15. Lewis, C. H. and Burgess, E. G., III. "Charts of Normal Shock Wave Properties in Imperfect Nitrogen." AEDC-TDR-64-104 (AD600844), May 1964.

16. Lewis, C. H. and Burgess, E. G., III. "Normal Shock Wave Properties in Imperfect Air and Nitrogen." AIAA J., Vol. 3, No. 3, March 1965, pp. 554-556.

17. Lewis, C. H. "Normal Shock Wave Properties in Imperfect Nitrogen." The Physics of Fluids, Vol. 8, No. 4, April 1965, pp. 765-766.

18. Feldman, S. "Hypersonic Gas Dynamic Charts for Equilibrium Air." AVCO Research Report 40, January 1957.

19. Bernstein, L. "Tabulated Solutions of the Equilibrium Gas Properties Behind Incident and Reflected Normal Shock-Waves in a Shock Tube." I - Nitrogen; II - Oxygen." ARC 22, 778, April 1961.

20. Humphrey, R. L. and Neel, C. A. "Tables of Thermodynamic Properties of Air from 90 to 1500°K." AEDC-TN-61-103 (AD262692), August 1961.

21. Little, W. J. and Neel, C. A. "Tables of the Thermodynamic Properties of Nitrogen from 100 to 1500°K." AEDC-TDR-62-170 (AD283441), September 1962.

22. Grabau, M. and Brahinsky, H. S. "Thermodynamic Properties of Nitrogen from 300 to 5000°K and from 1 to 1000 Amagats." AEDC-TR-66-69, to be published.

23. Lewis, C. H. and Burgess, E. G., III. "Charts of Normal Shock Wave Properties in Imperfect Air (Supplement: $M_S = 1$ to 10)." AEDC-TR-65-196 (AD470664), September 1965.

24. Fay, J. A. and Riddell, F. R. "Theory of Stagnation Point Heat Transfer in Dissociated Air." J. Aero. Sci., Vol. 25, No. 2, February 1958, pp. 73-85, 121.

25. Lewis, C. H. and Burgess, E. G. III. "Charts of Sphere Stagnation Heat-Transfer Rate in Air and Nitrogen at High Temperatures." AIAA J., Vol. 1, No. 8, August 1963, pp. 1927-1929.

26. Lewis, C. H. and Burgess, E. G., III. "Altitude-Velocity, Table and Charts for Imperfect Air." AEDC-TDR-64-214 (AD454070), January 1965. Also AIAA Journal, Vol. 3, No. 6, June 1965, pp. 1176-1177.

27. Ahtye, W. F. and Peng, T-C. "Approximations for the Thermodynamic and Transport Properties of High-Temperature Nitrogen with Shock-Tube Applications." NASA TND-1303, July 1962.

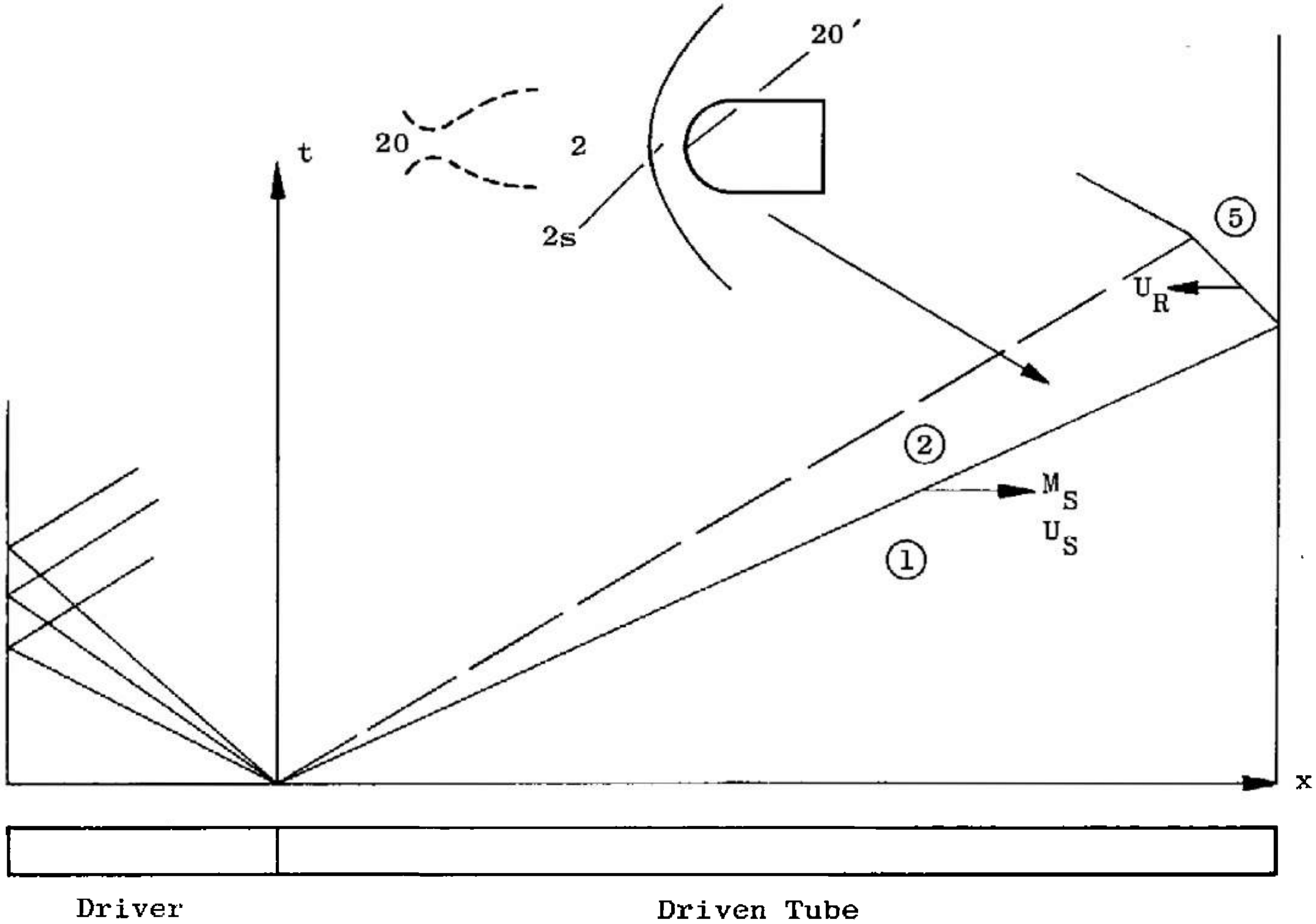
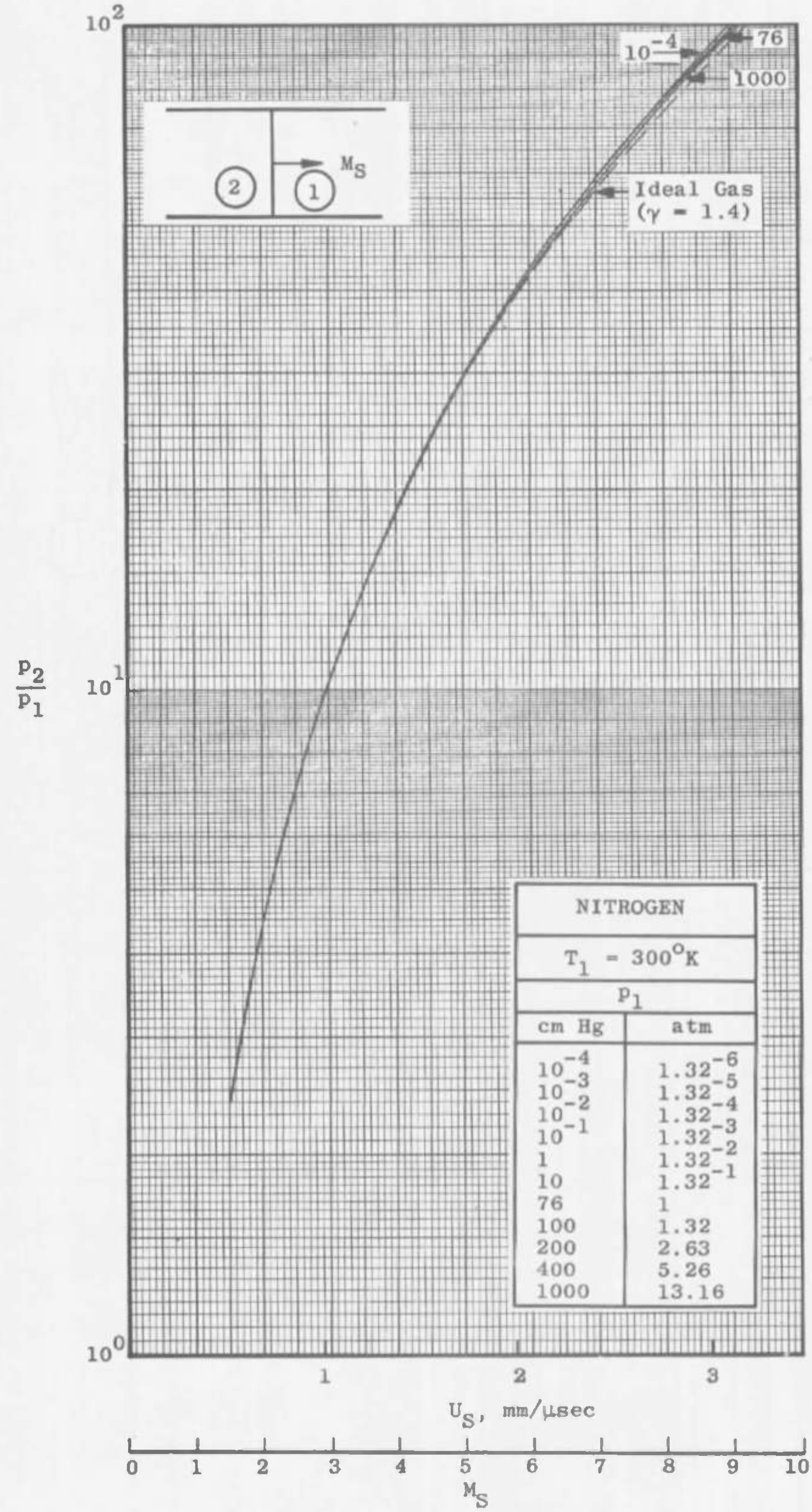
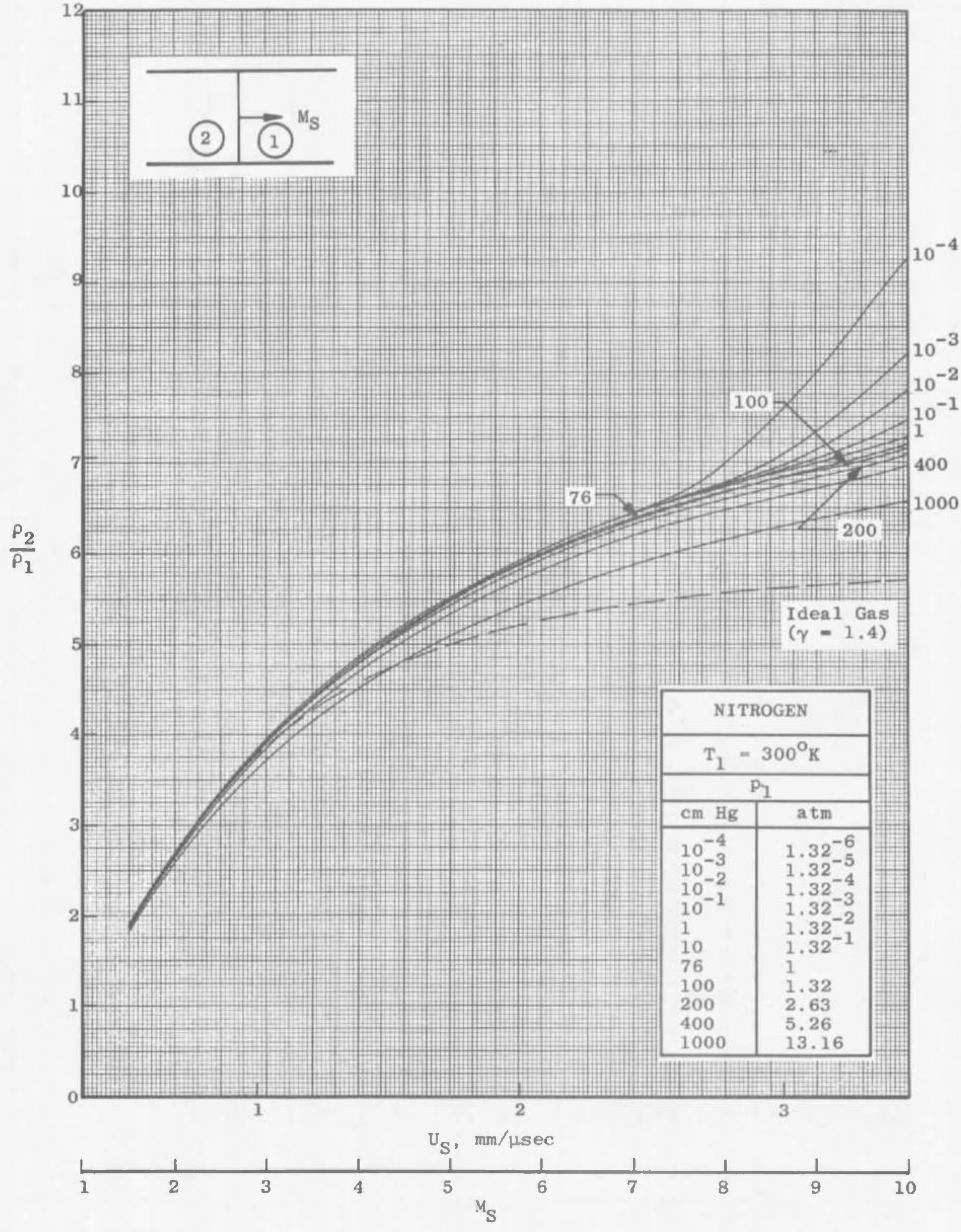


Fig. 1 Shock Tube and Normal Shock Nomenclature



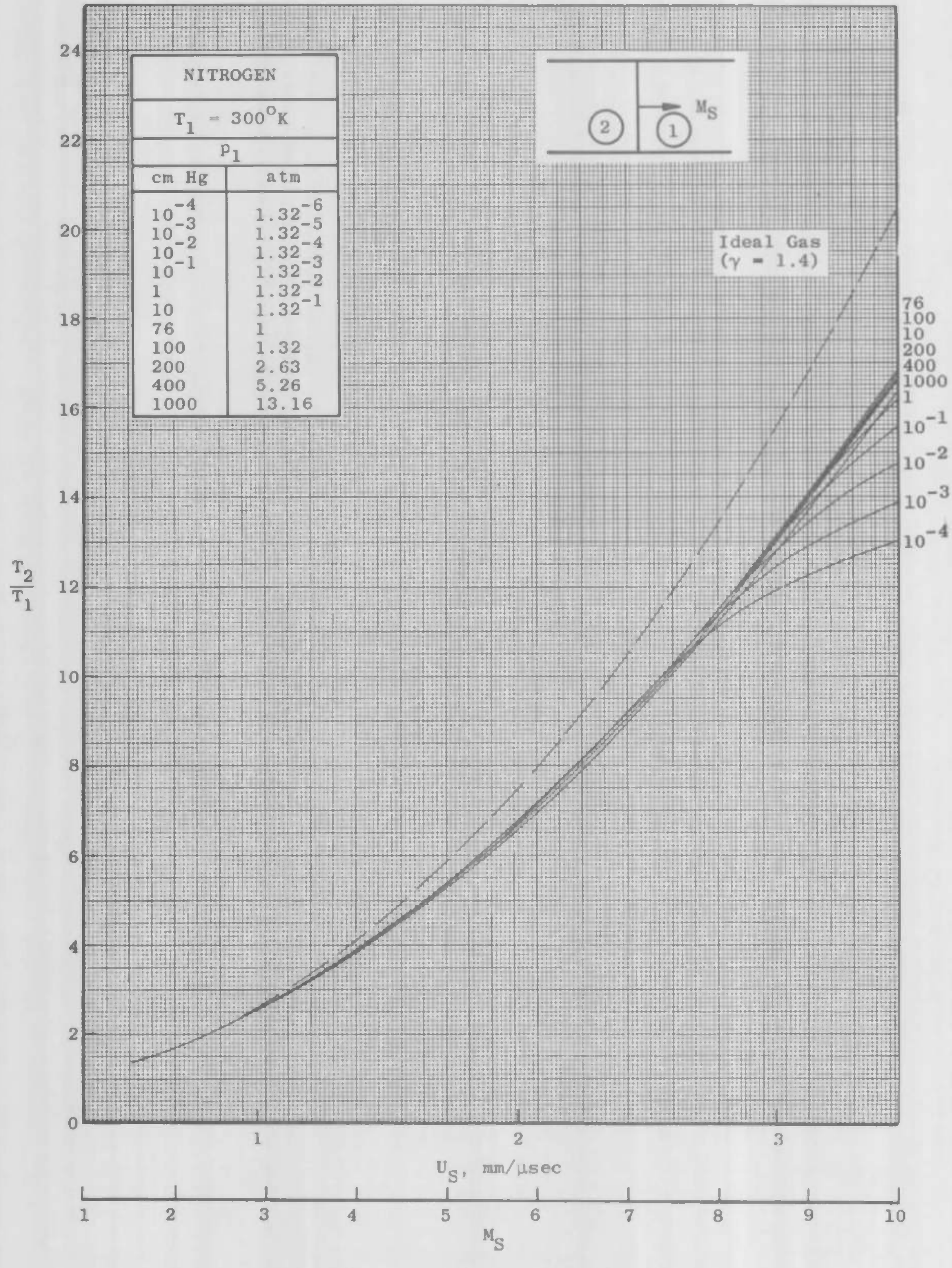
a. p_2/p_1 against Shock Mach Number M_S

Fig. 2 Conditions Behind an Incident Shock Wave into Nitrogen at 300°K



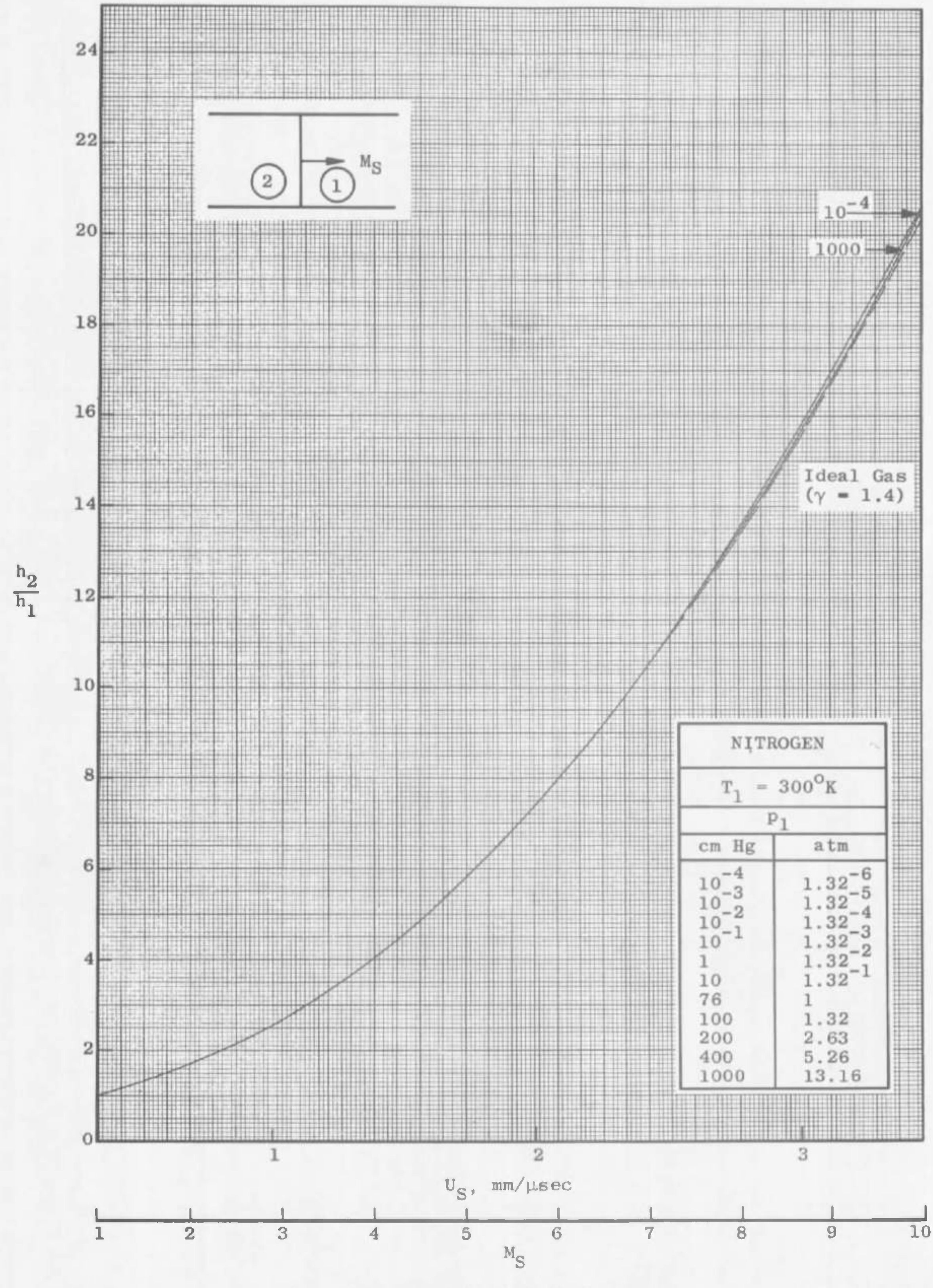
b. ρ_2/ρ_1 against Shock Mach Number M_S

Fig. 2 Continued



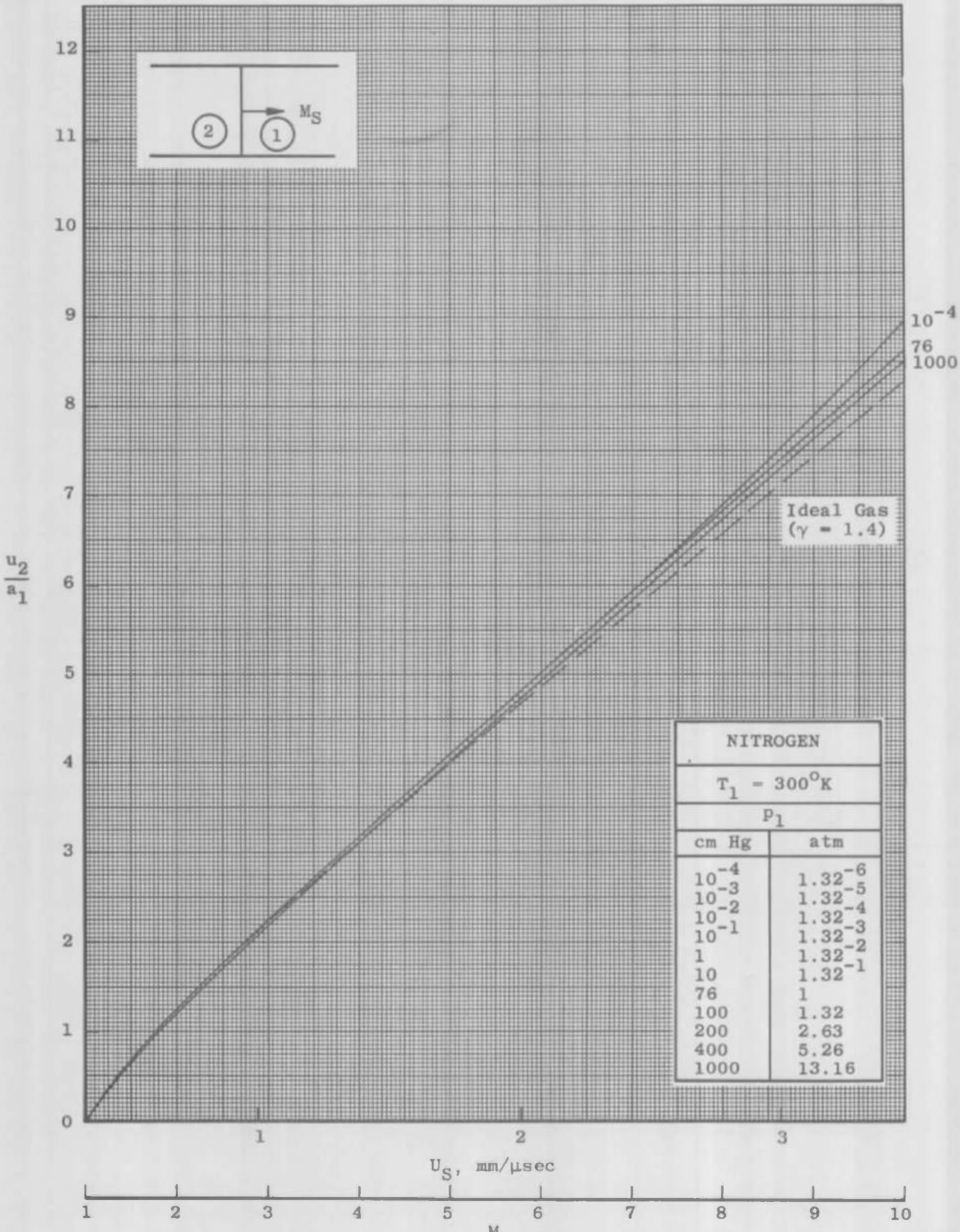
c. T_2/T_1 against Shock Mach Number M_S

Fig. 2 Continued



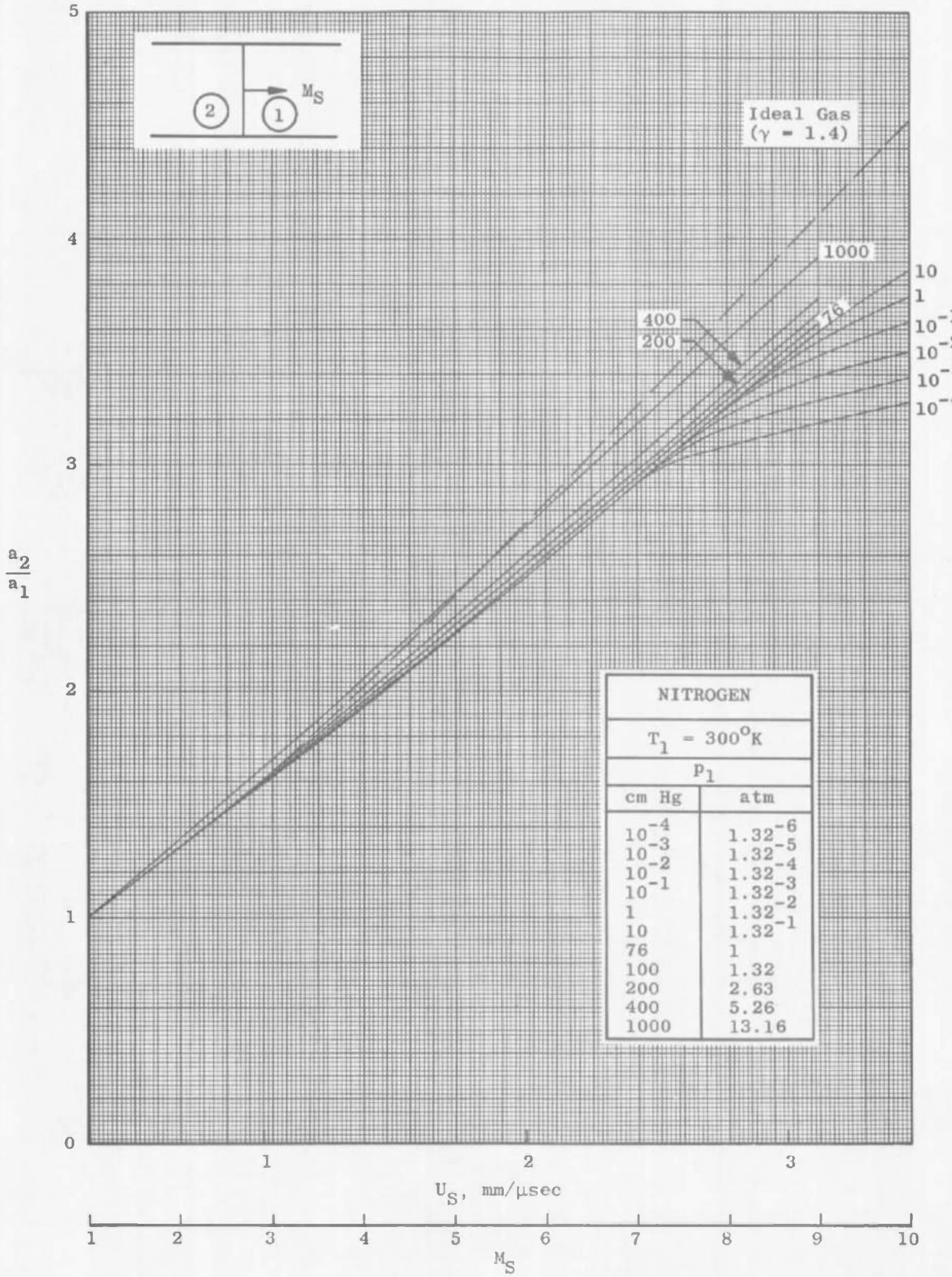
d. h_2/h_1 against Shock Mach Number M_S

Fig. 2 Continued



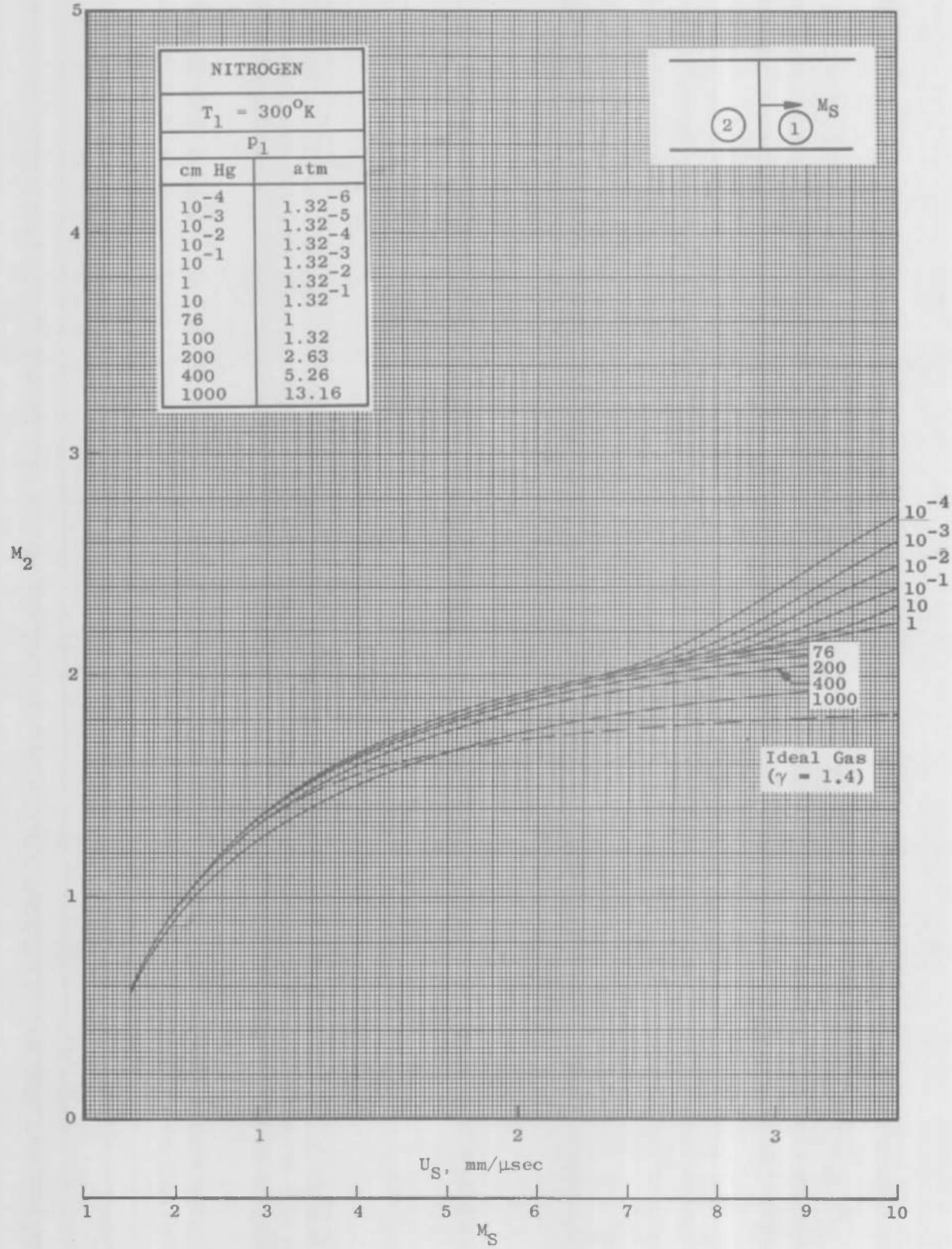
e. u_2/a_1 against Shock Mach Number M_S

Fig. 2 Continued



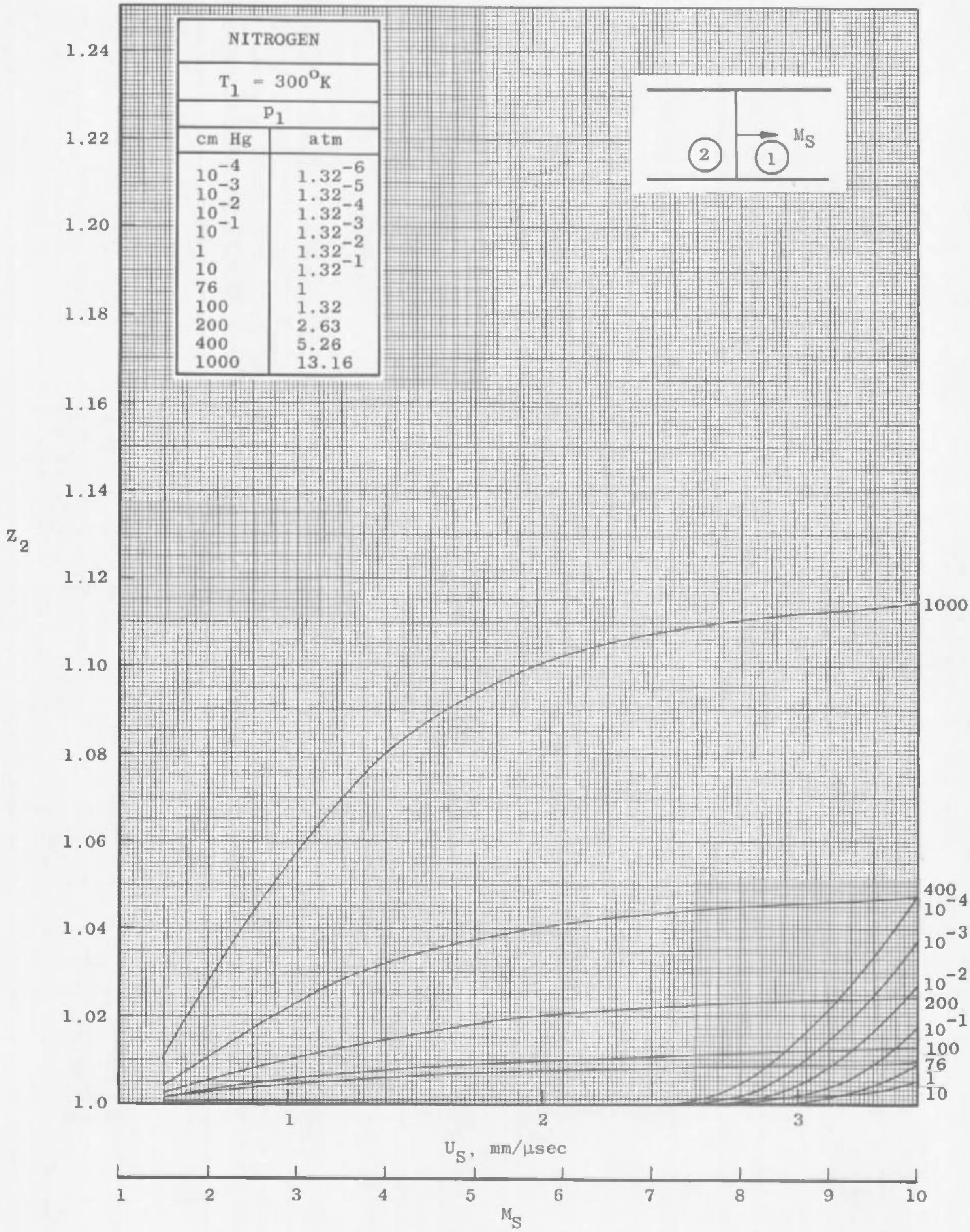
f. a_2/a_1 against Shock Mach Number M_S

Fig. 2 Continued



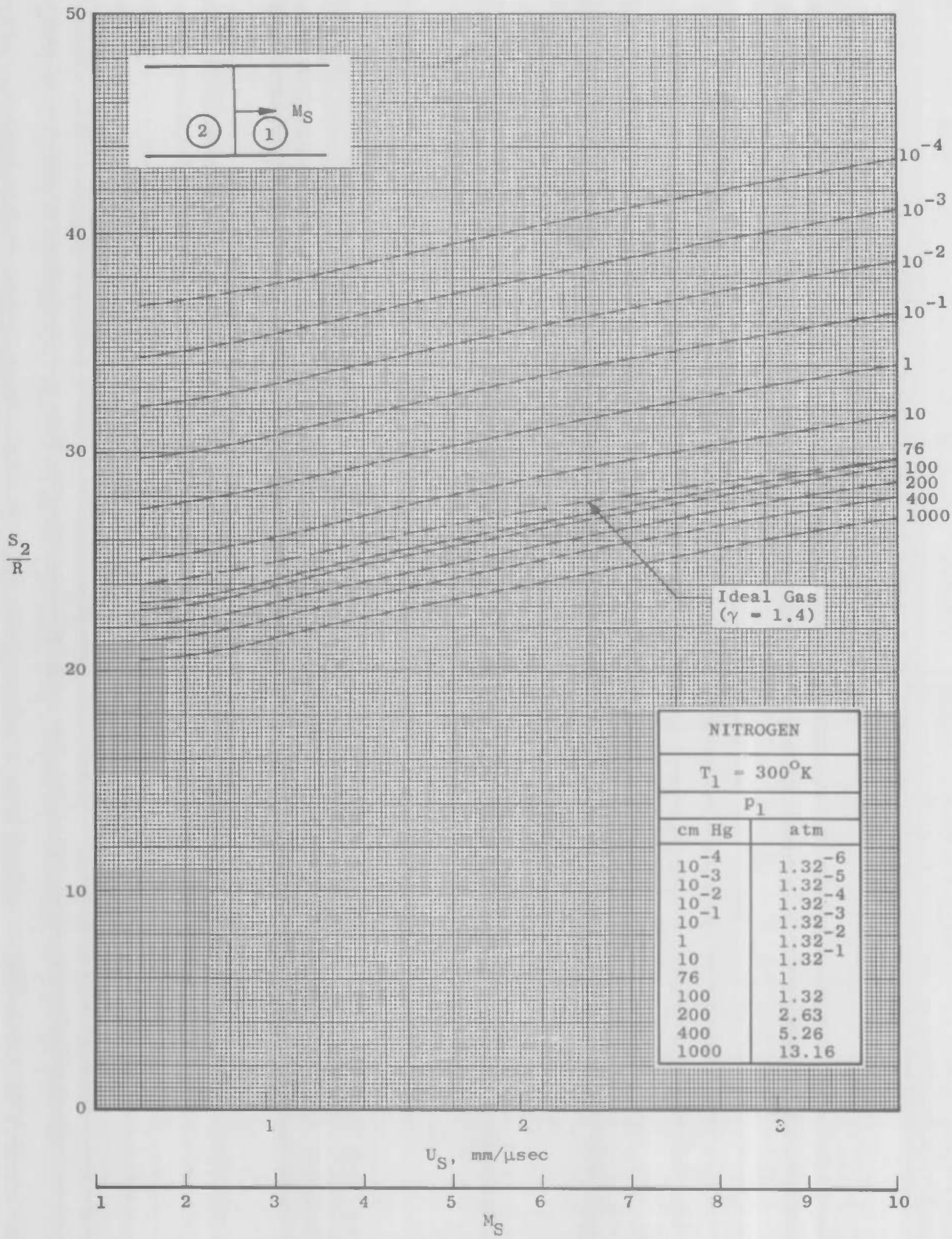
g. M_2 against Shock Mach Number M_S

Fig. 2 Continued



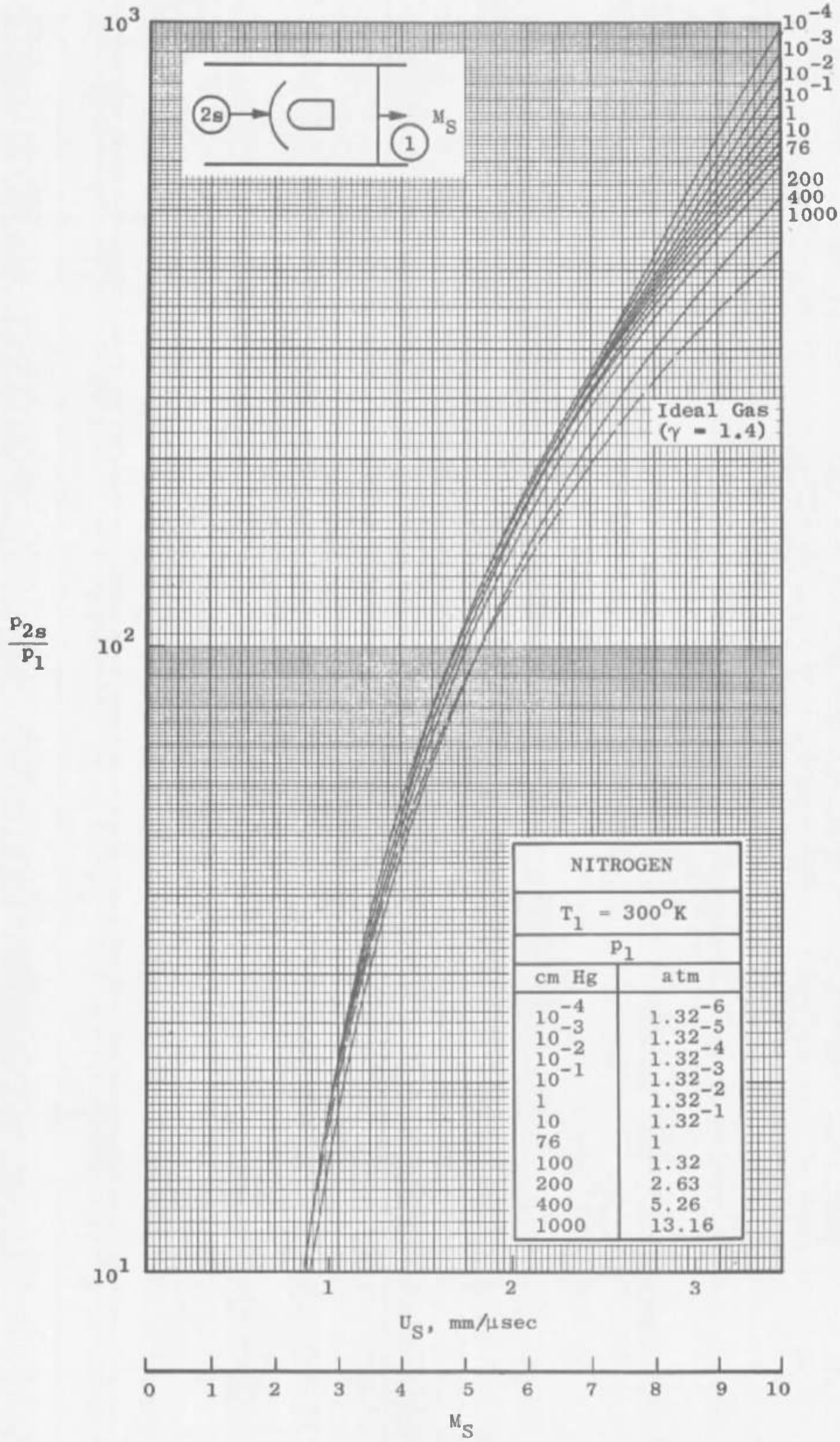
h. Z_2 against Shock Mach Number M_S

Fig. 2 Continued



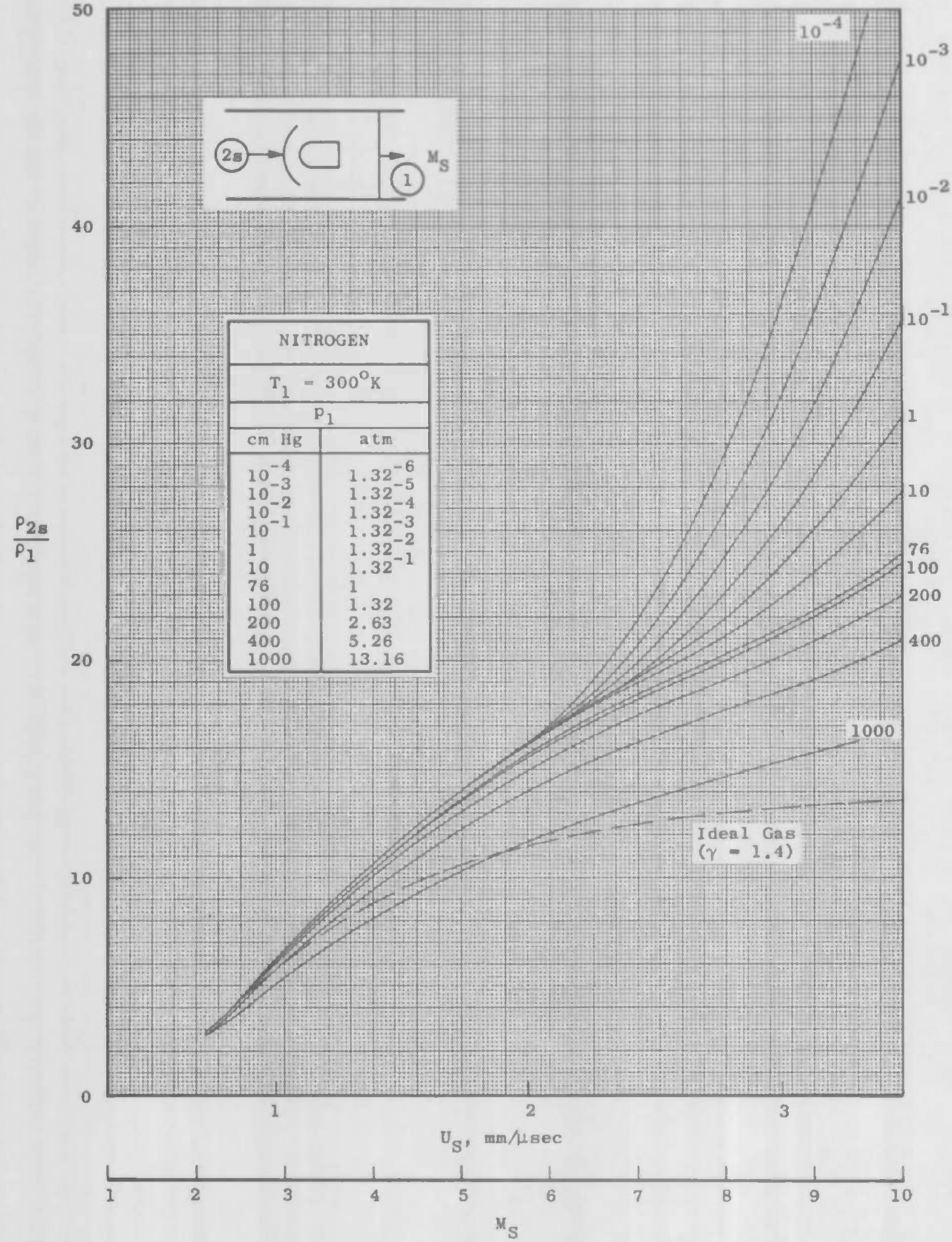
i. S_2/R against Shock Mach Number M_S

Fig. 2 Concluded



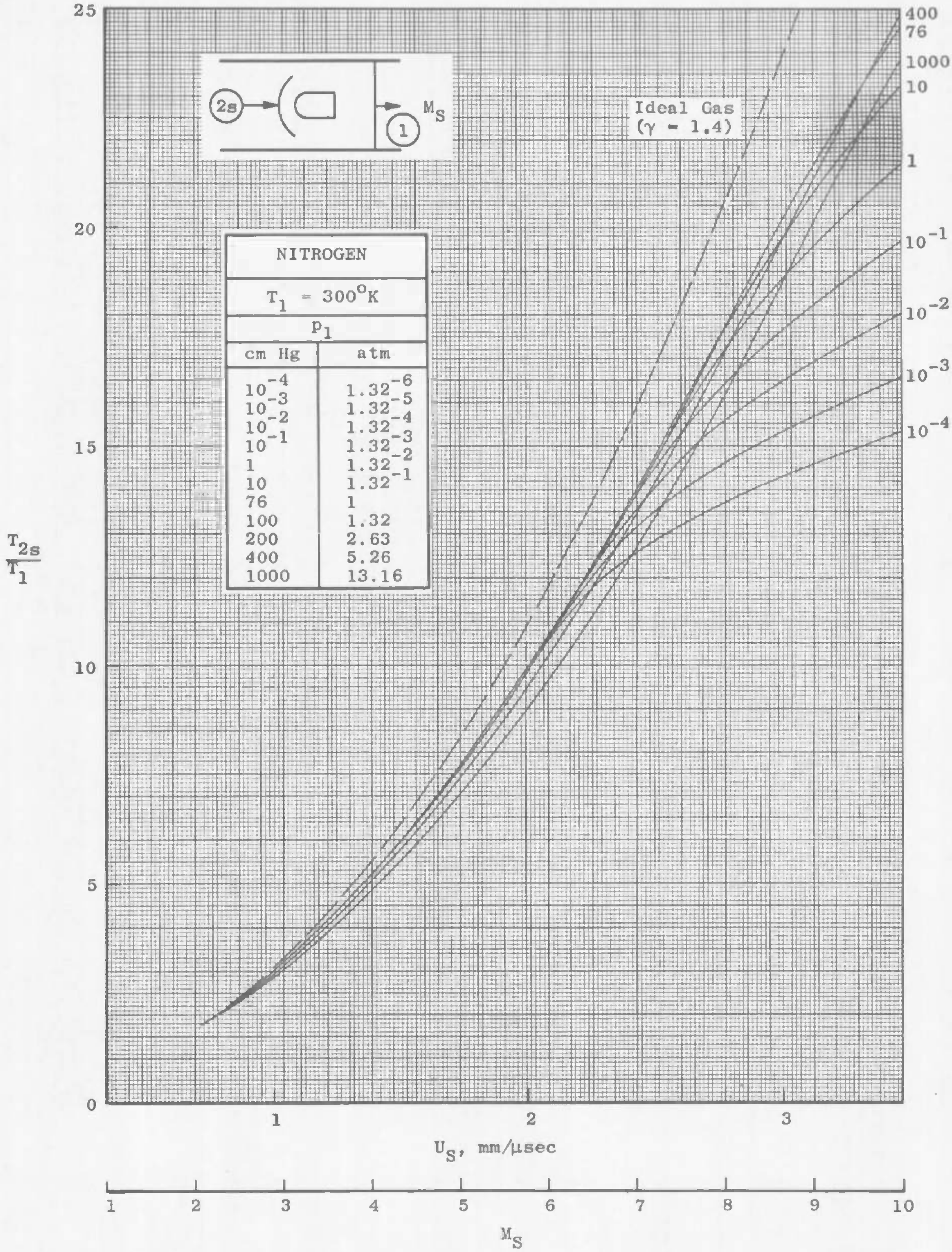
a. p_{2s}/p_1 against Incident Shock Mach Number M_S

Fig. 3 Condition Behind a Standing Shock Wave in Region 2



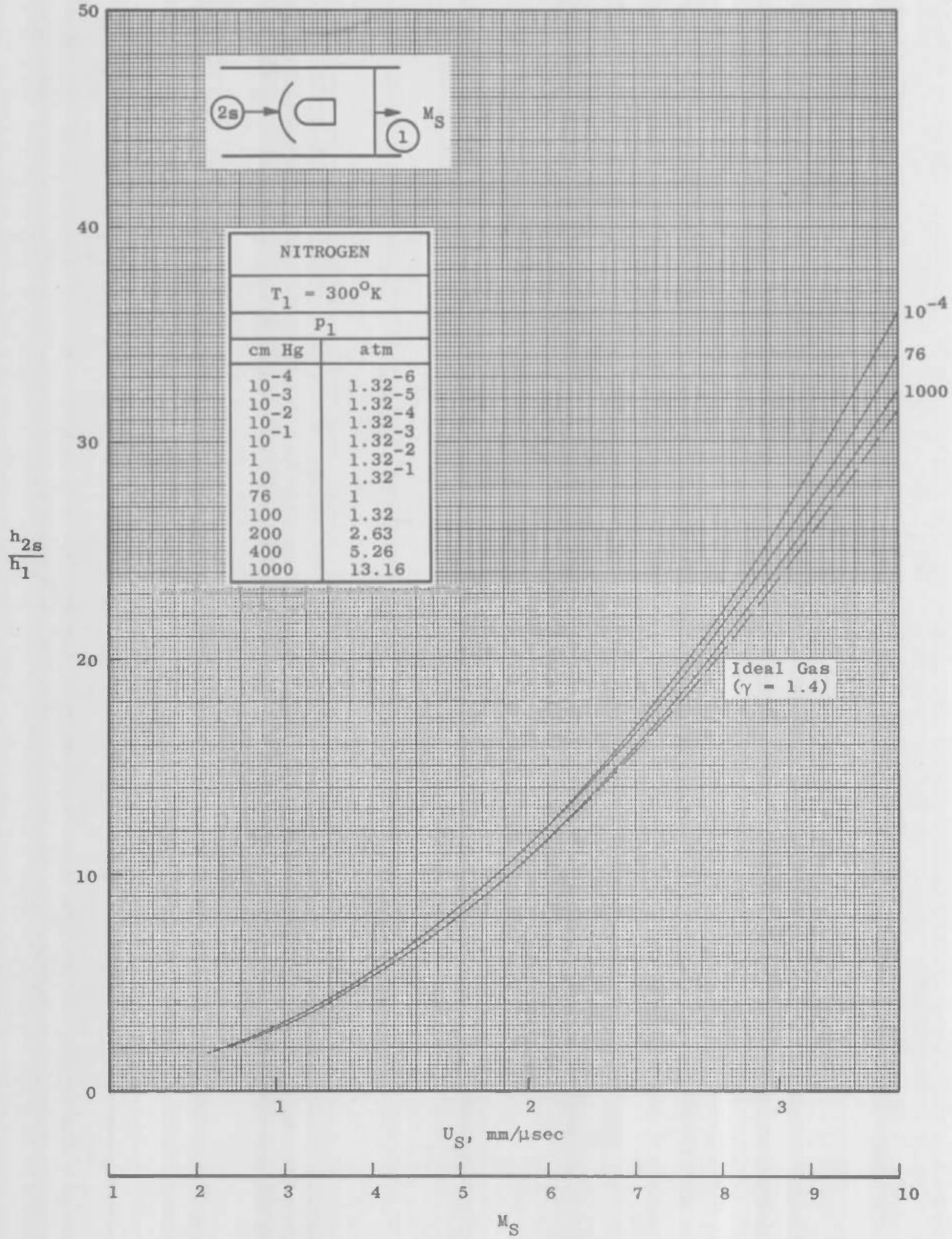
b. ρ_{2s}/ρ_1 against Incident Shock Mach Number M_S

Fig. 3 Continued



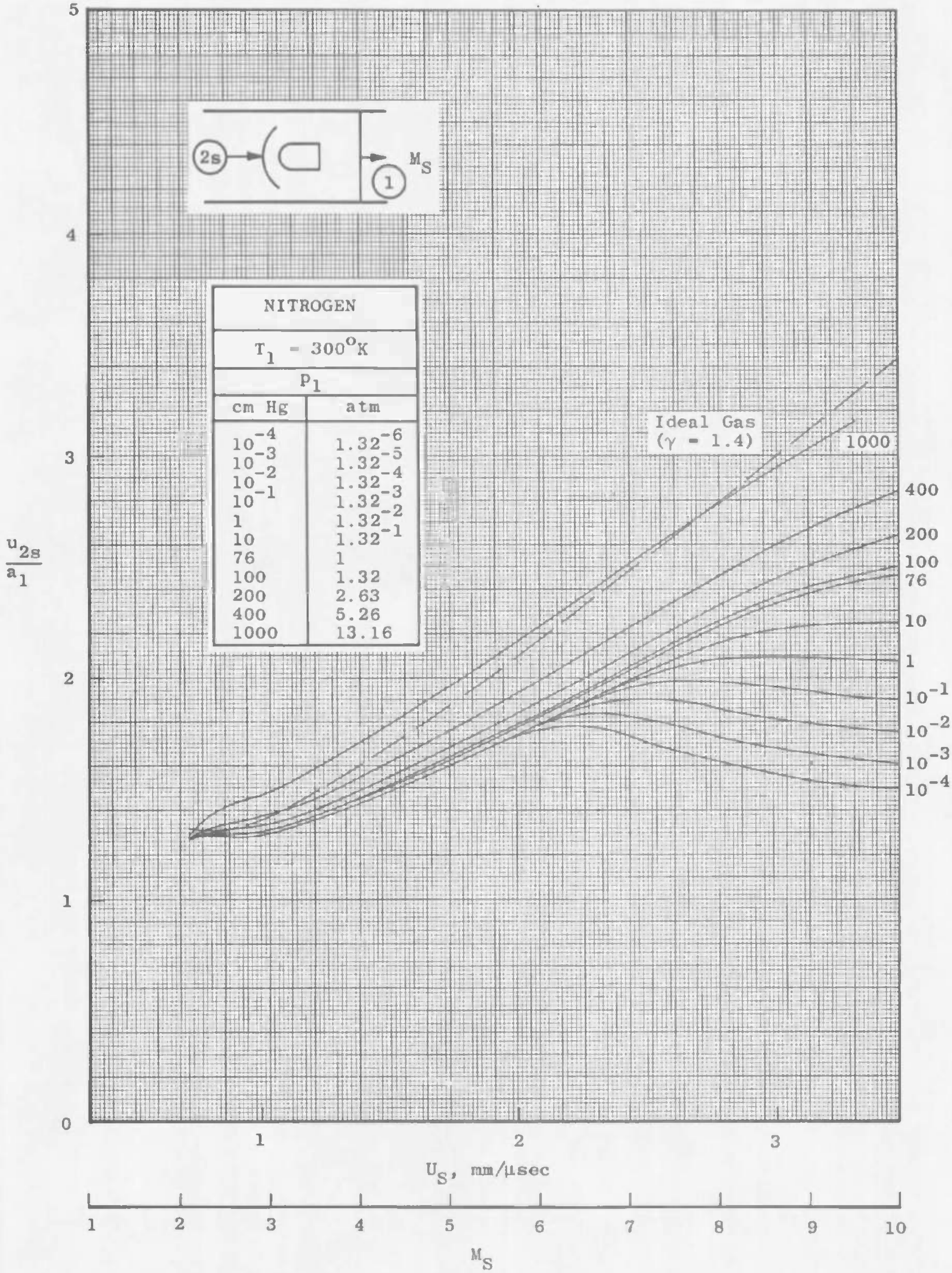
c. T_{2s}/T_1 against Incident Shock Mach Number M_S

Fig. 3 Continued



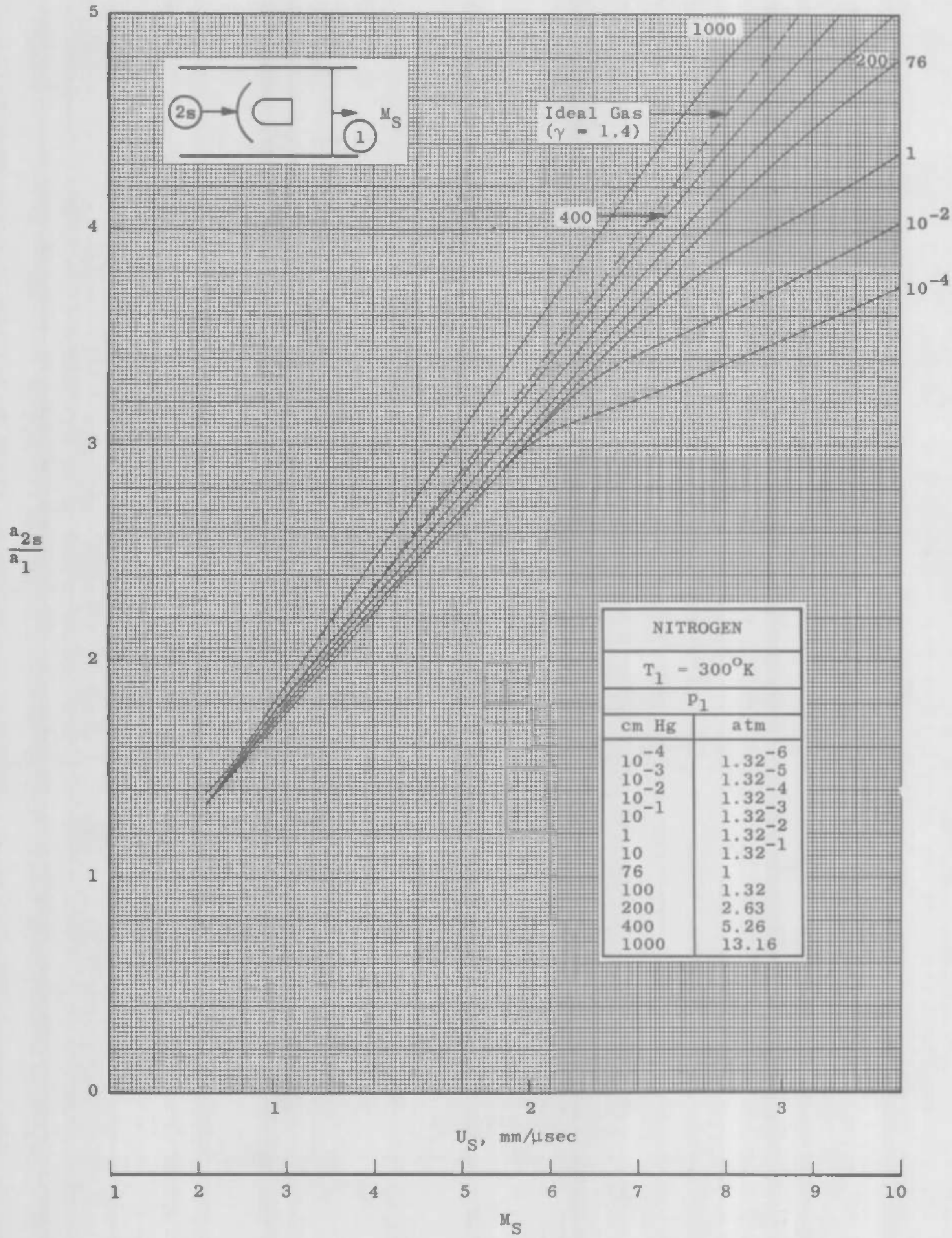
d. h_{2s}/h_1 against Incident Shock Mach Number M_S

Fig. 3 Continued



e. u_{2s}/a_1 against Incident Shock Mach Number M_S

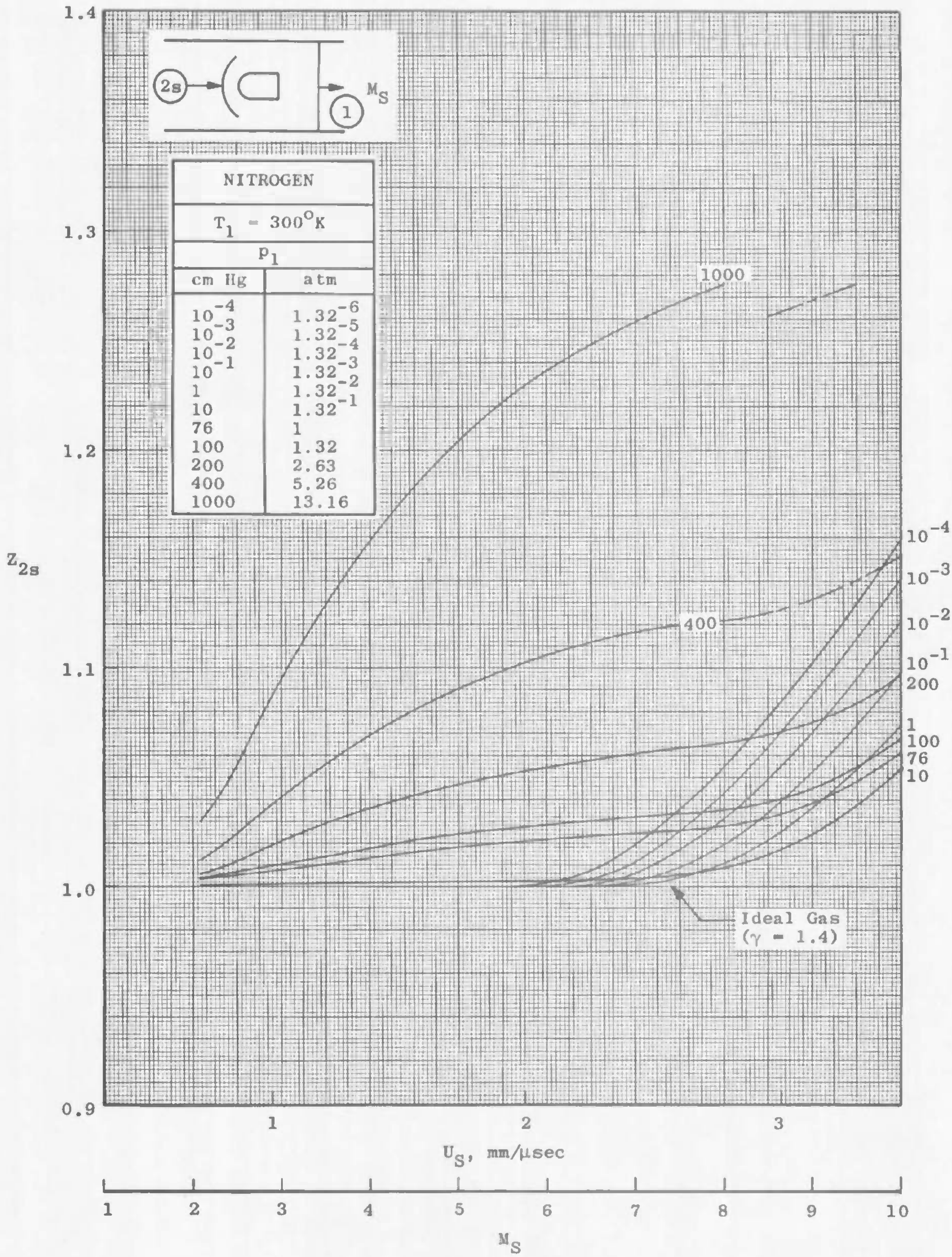
Fig. 3 Continued



NITROGEN	
$T_1 = 300^oK$	
p_1	
cm Hg	atm
10^{-4}	1.32^{-6}
10^{-3}	1.32^{-5}
10^{-2}	1.32^{-4}
10^{-1}	1.32^{-3}
1	1.32^{-2}
10	1.32^{-1}
76	1
100	1.32
200	2.63
400	5.26
1000	13.16

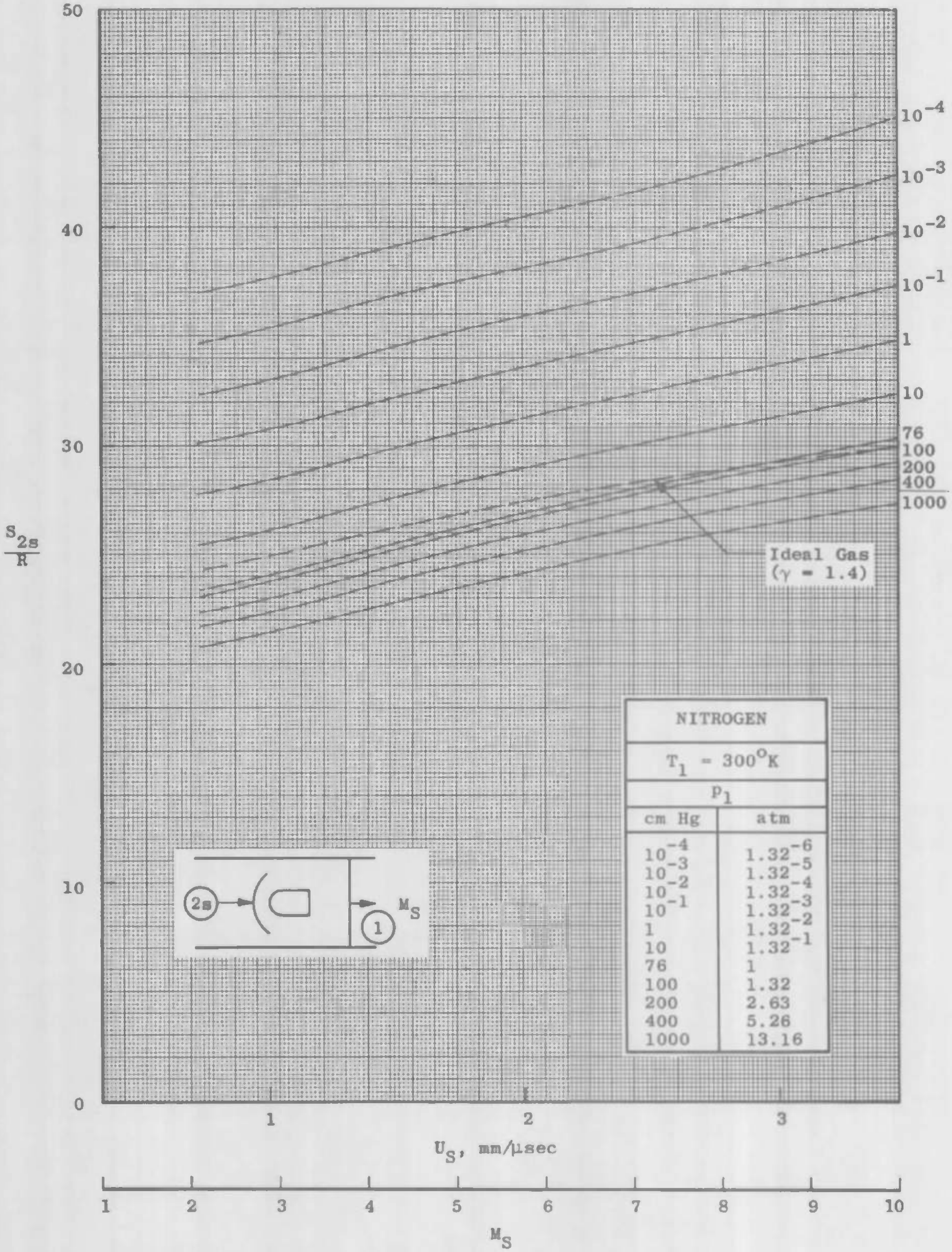
f. a_{2s}/a_1 against Incident Shock Mach Number M_S

Fig. 3 Continued



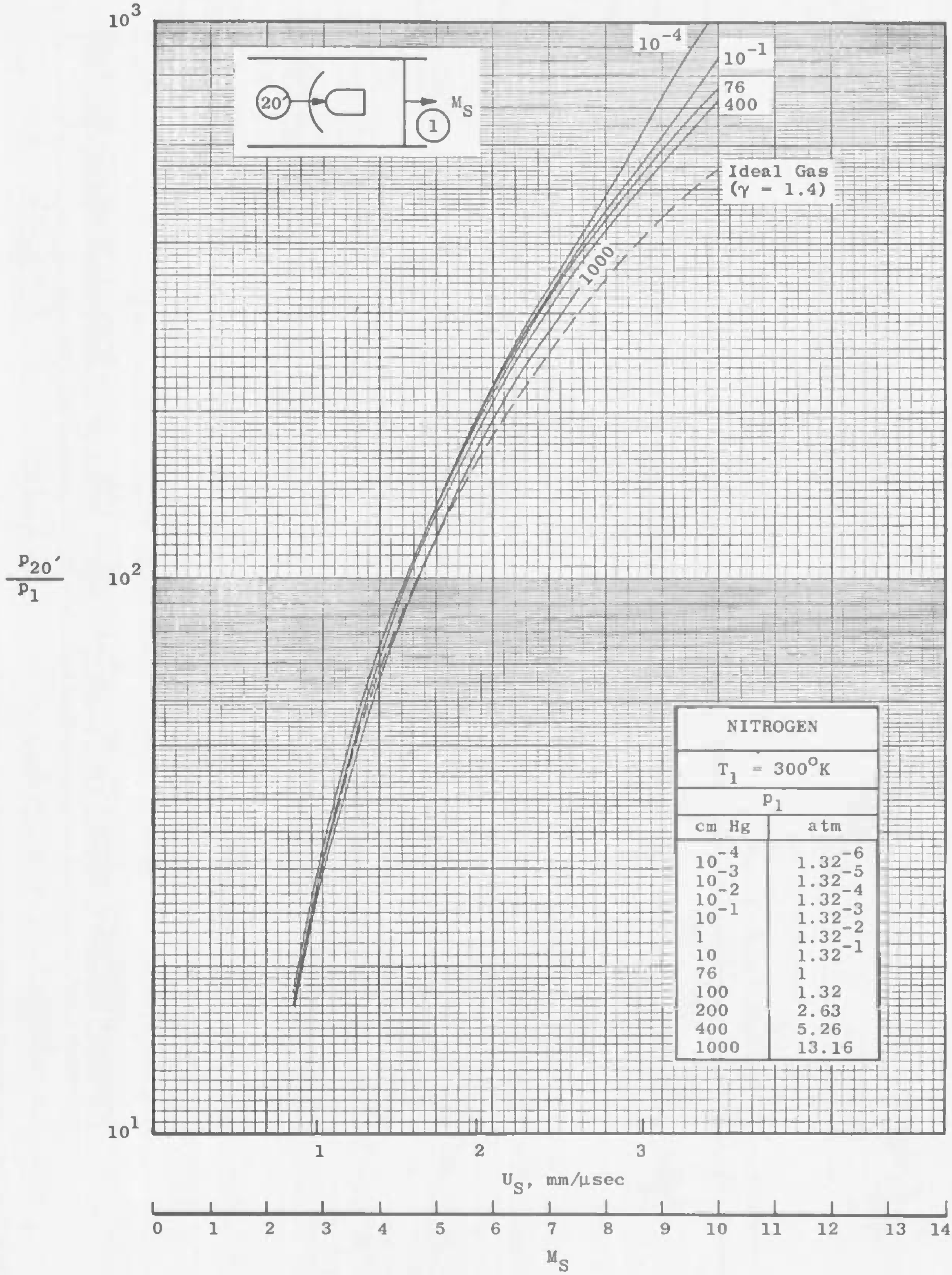
g. Z_{2s} against Incident Shock Mach Number M_S

Fig. 3 Continued



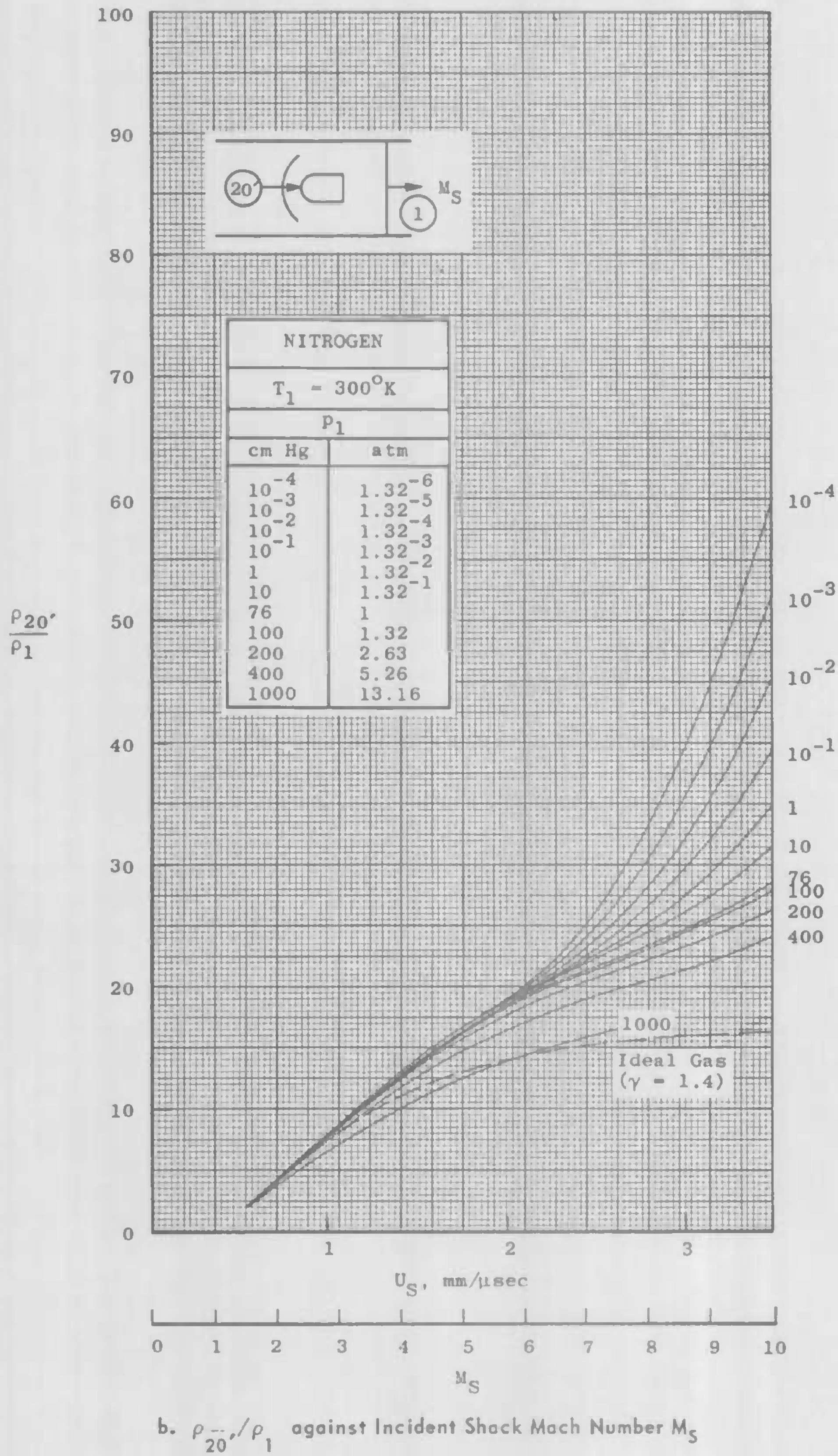
h. S_{2s}/R against Incident Shock Mach Number M_S

Fig. 3 Concluded



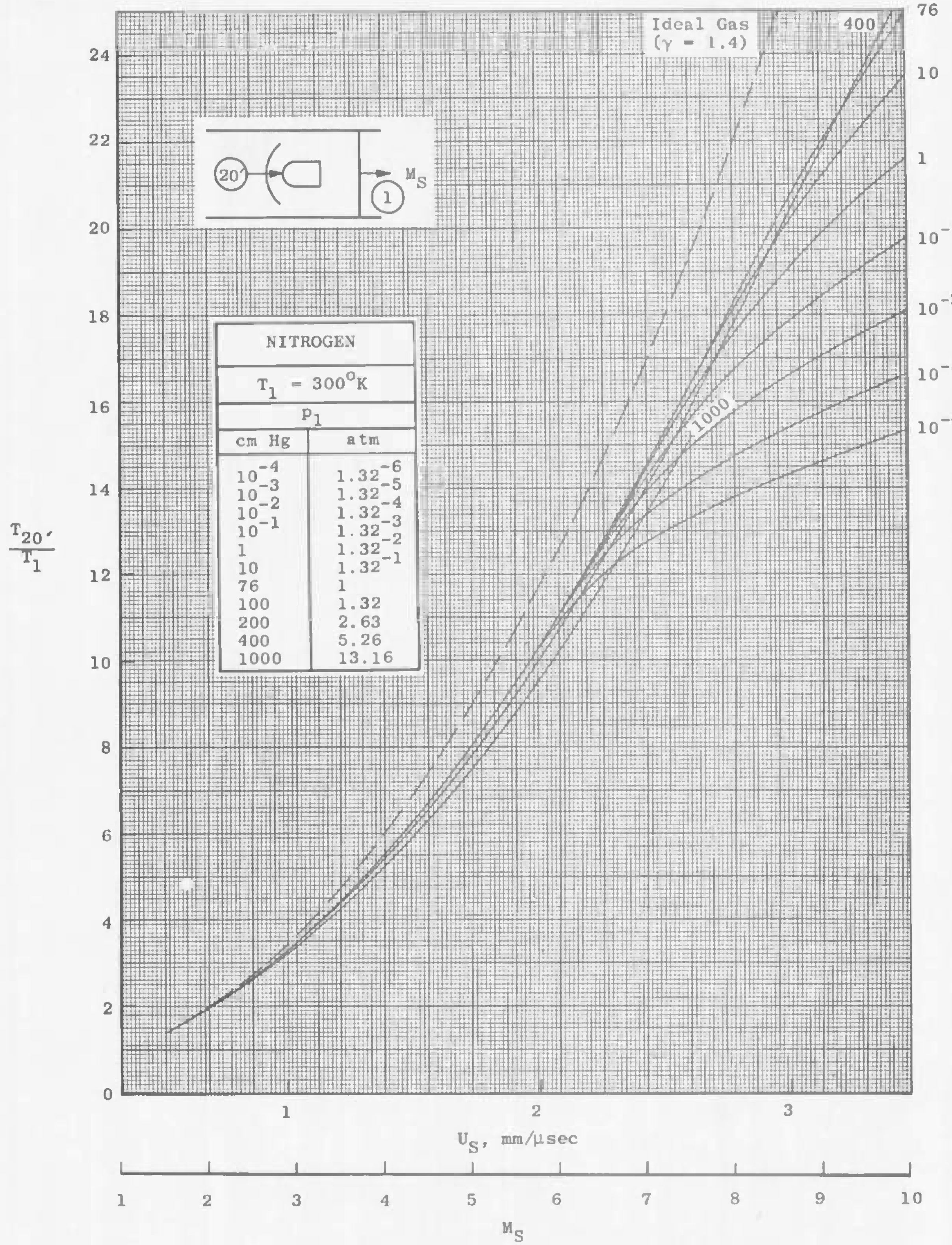
a. $p_{20'}/p_1$ against Incident Shock Mach Number M_S

Fig. 4 Stagnation Conditions Downstream of a Standing Shock Wave in Region 2



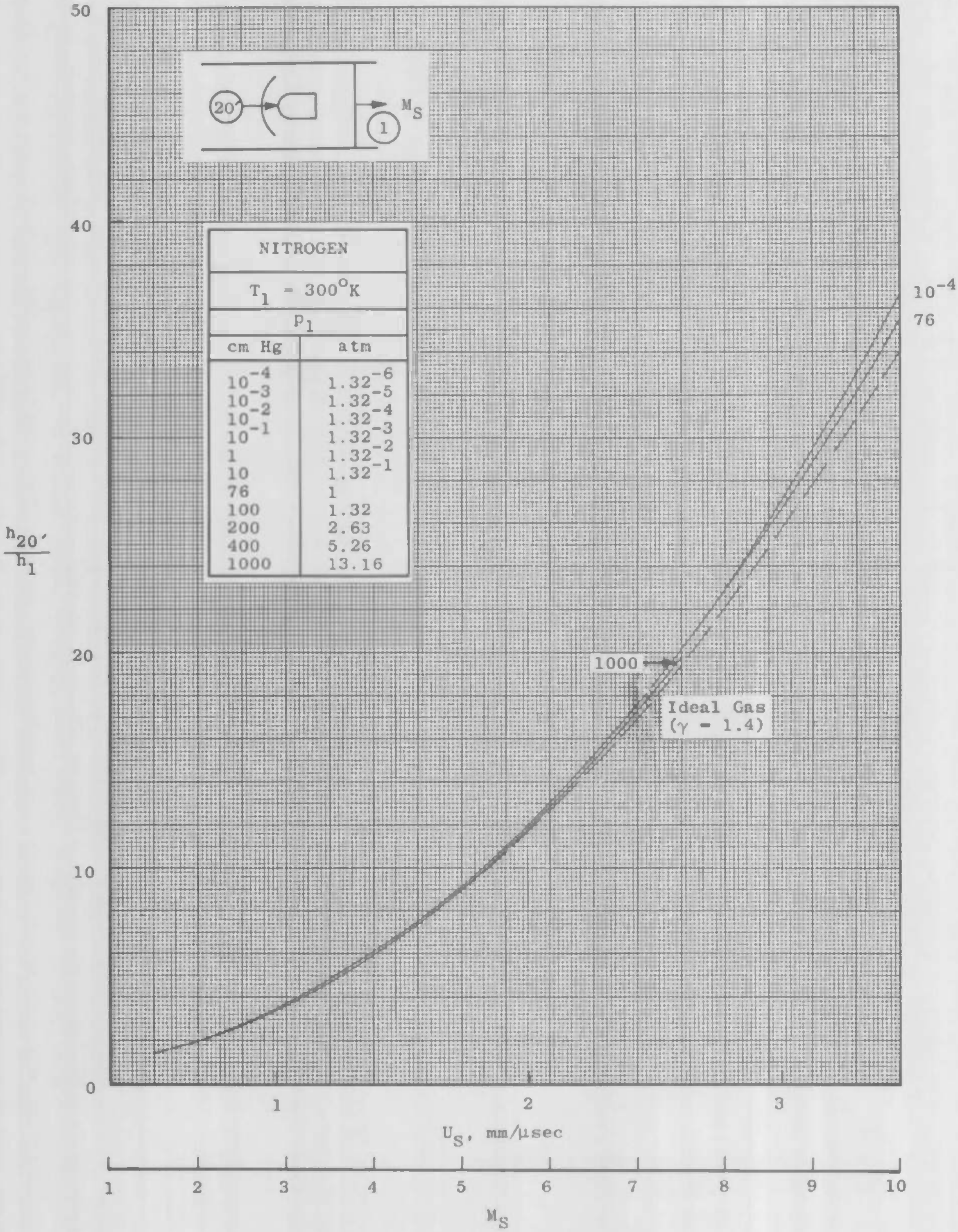
b. $\rho_{20'}/\rho_1$ against Incident Shock Mach Number M_S

Fig. 4 Continued



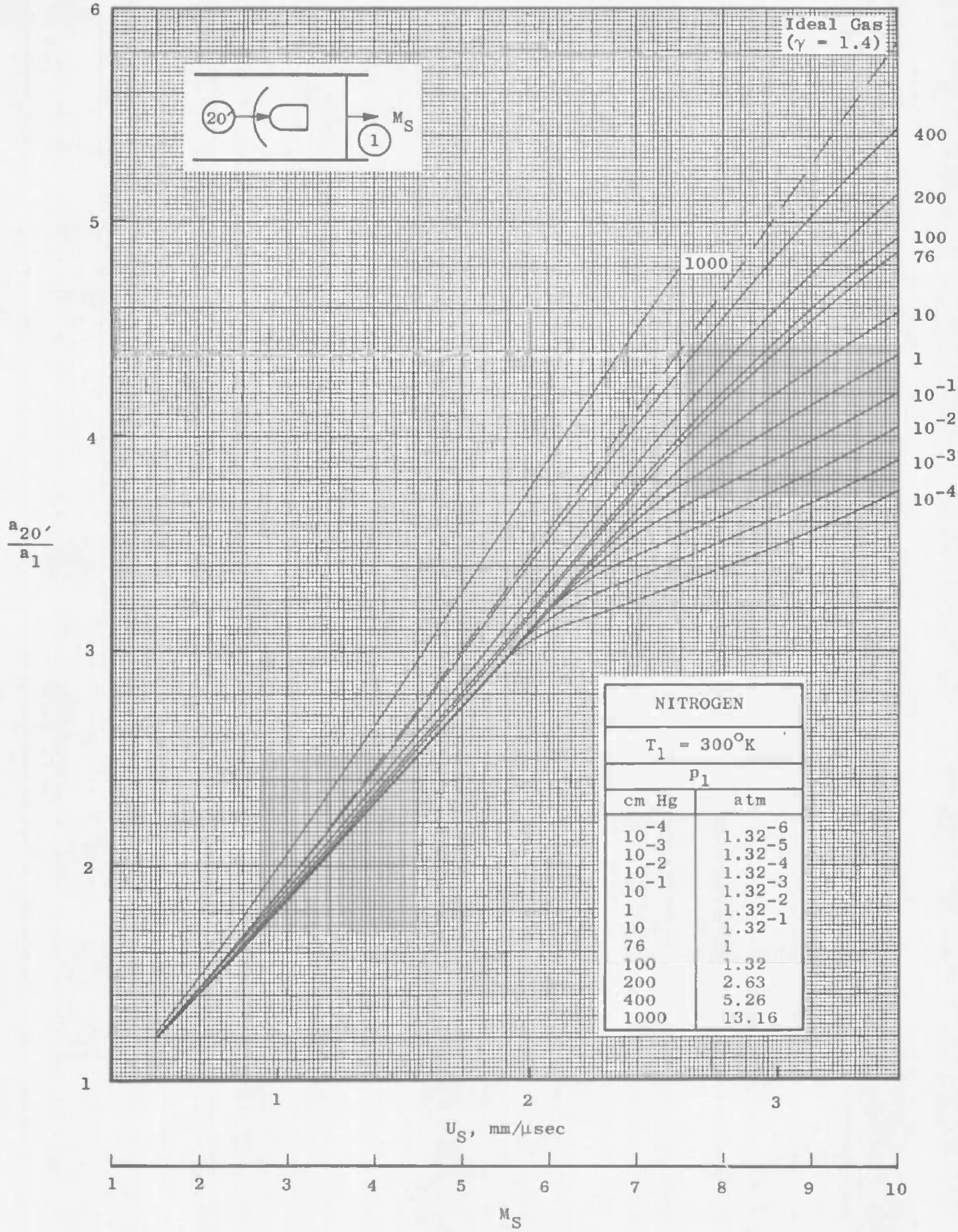
c. $T_{20'}/T_1$ against Incident Shock Mach Number M_S

Fig. 4 Continued



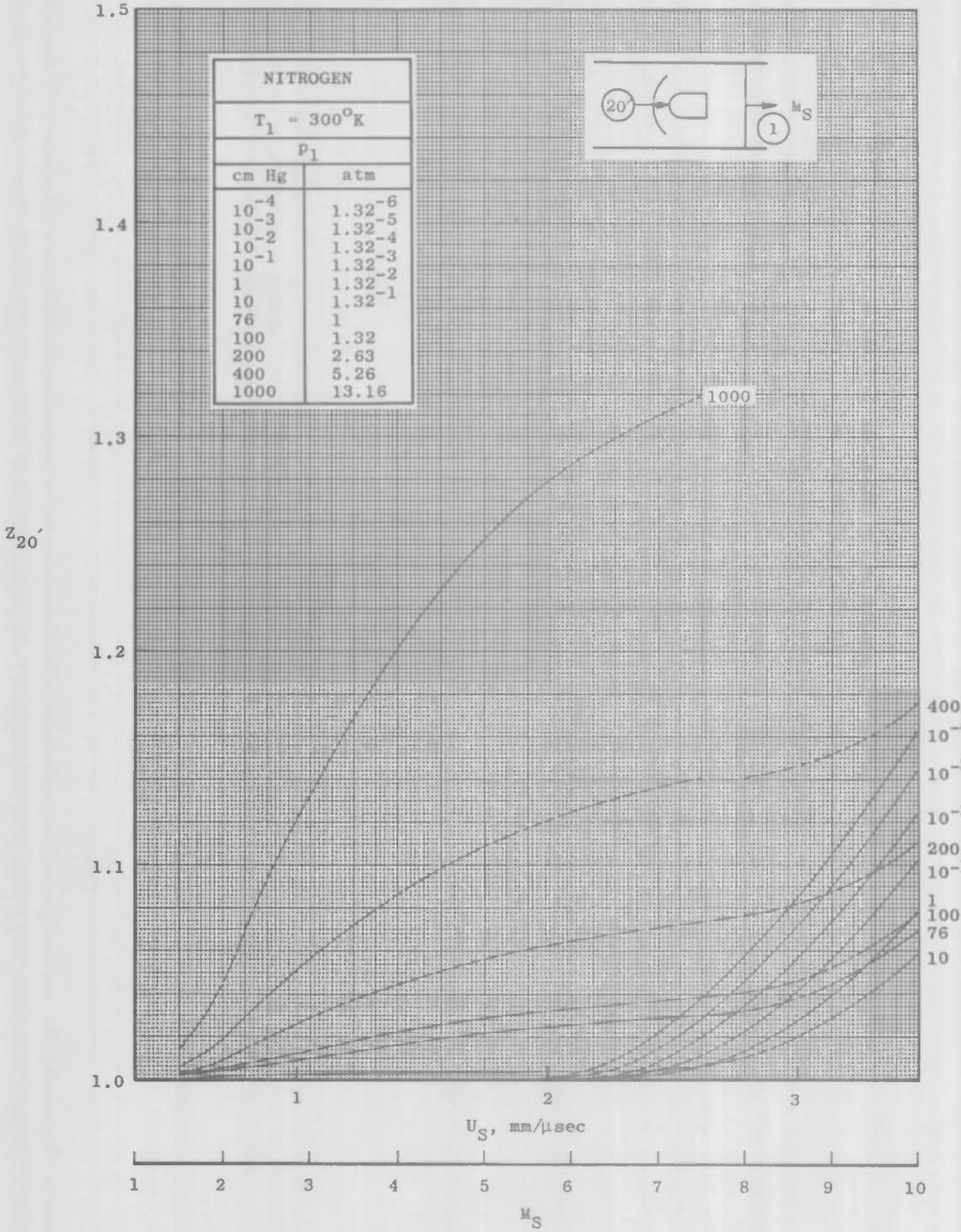
d. $h_{20'}/h_1$ against Incident Shock Mach Number M_S

Fig. 4 Continued



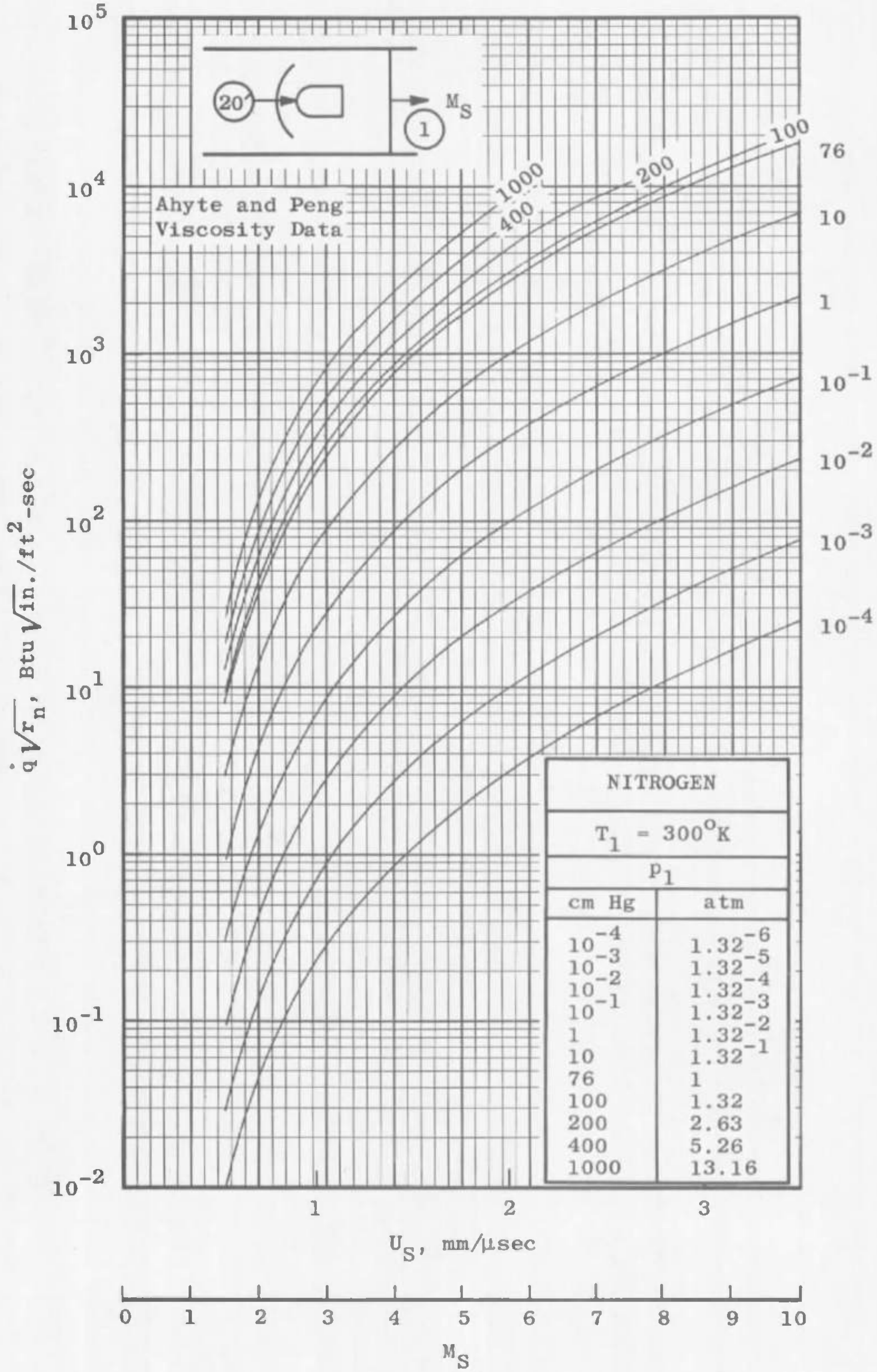
e. $a_{20'}/a_1$ against Incident Shock Mach Number M_S

Fig. 4 Continued



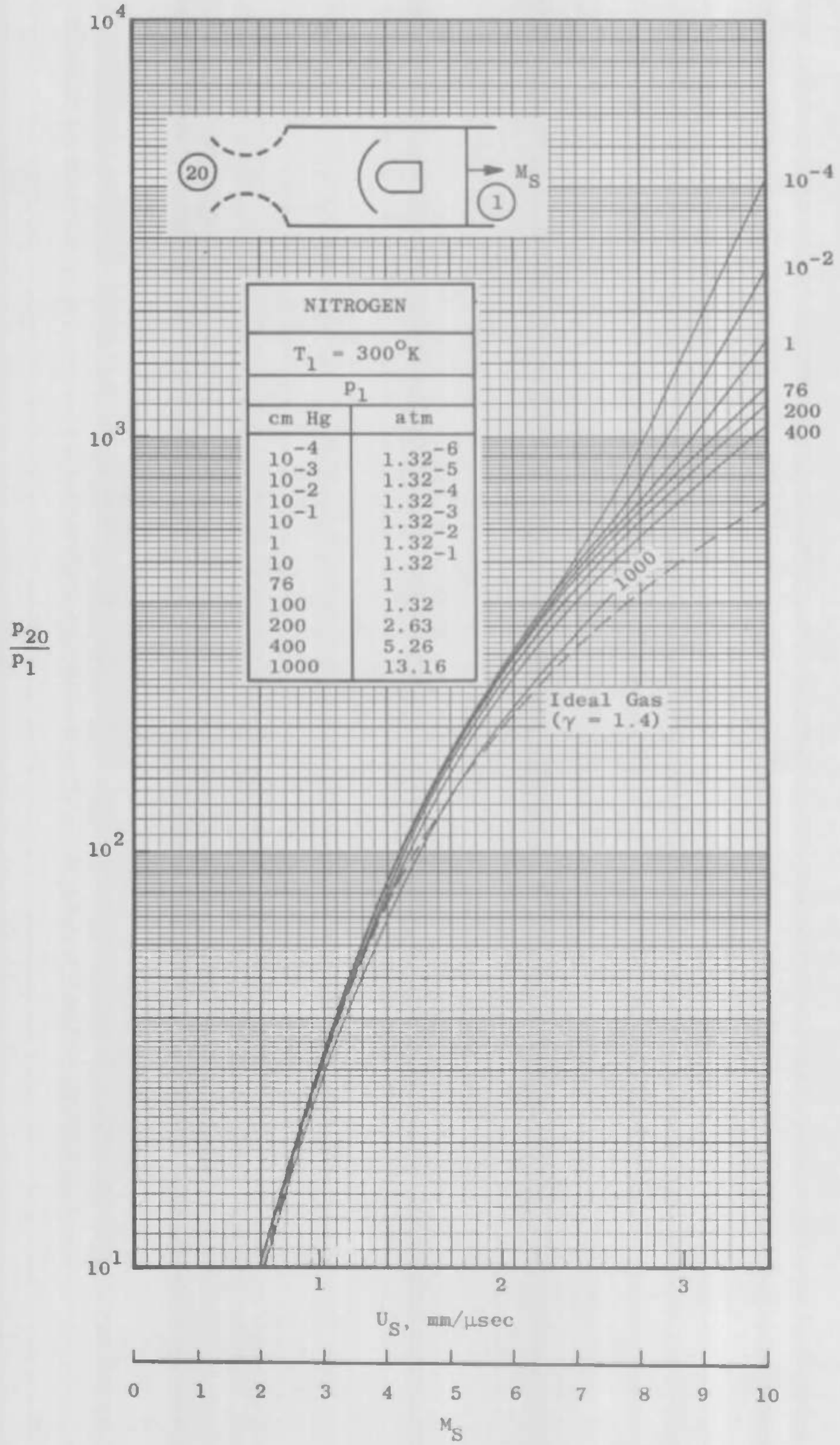
f. $Z_{20'}$ against Incident Shock Mach Number M_S

Fig. 4 Continued



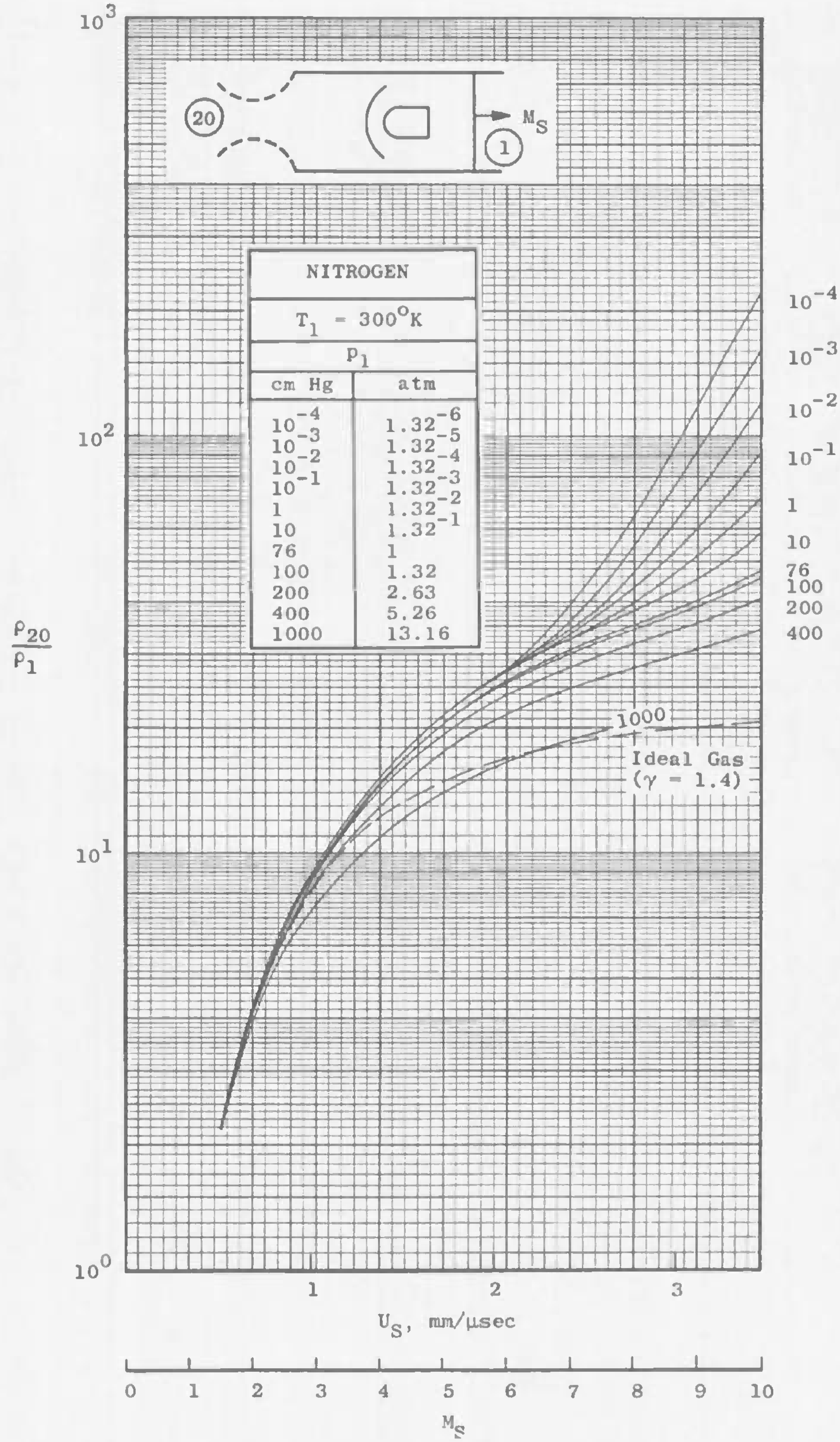
g. $\dot{q}\sqrt{r_n}$ (Fay-Riddell) against Incident Shock Mach Number M_S

Fig. 4 Concluded



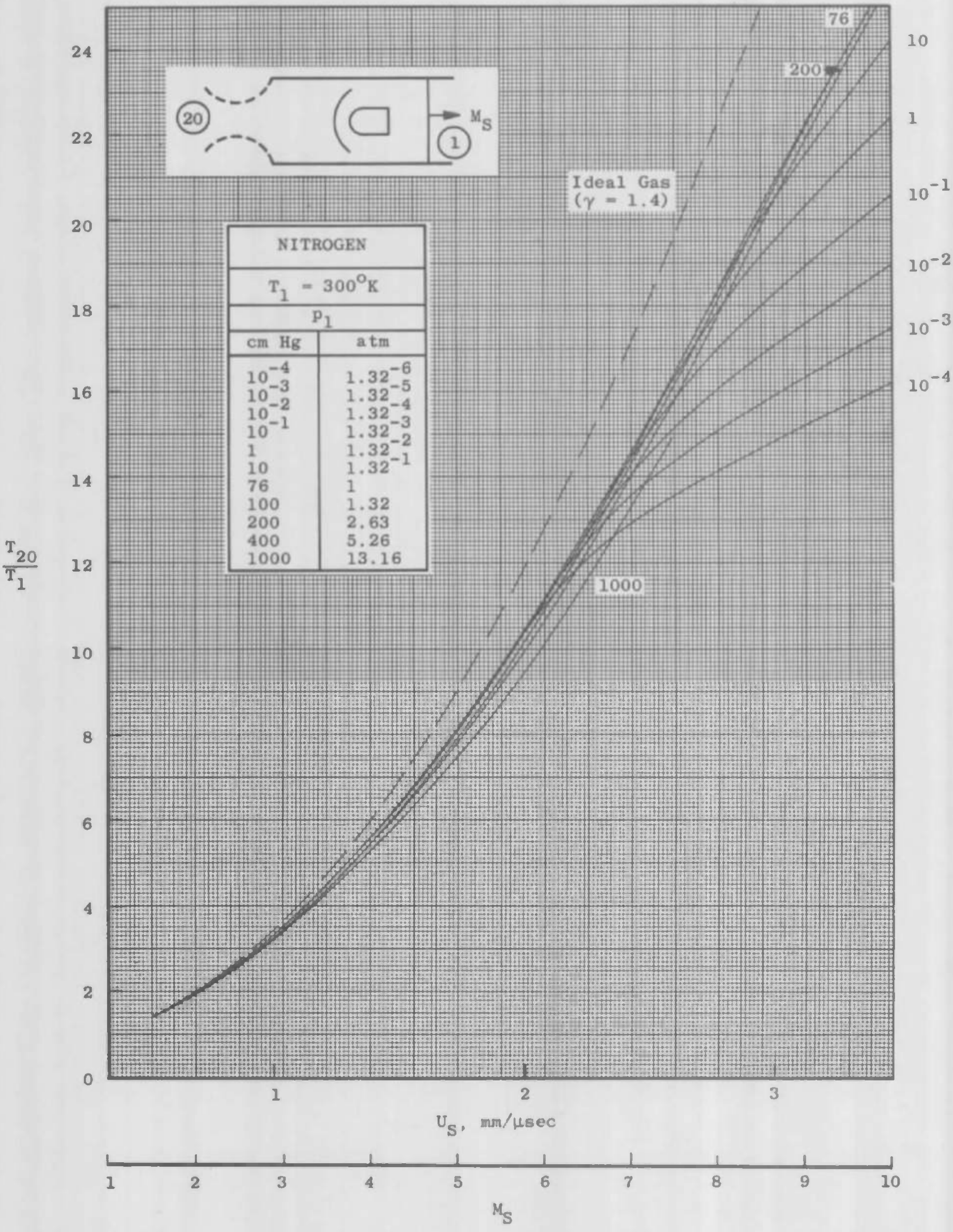
a. p_{20}/p_1 against Incident Shock Mach Number M_S

Fig. 5 Stagnation Conditions Upstream of a Standing Shock Wave in Region 2



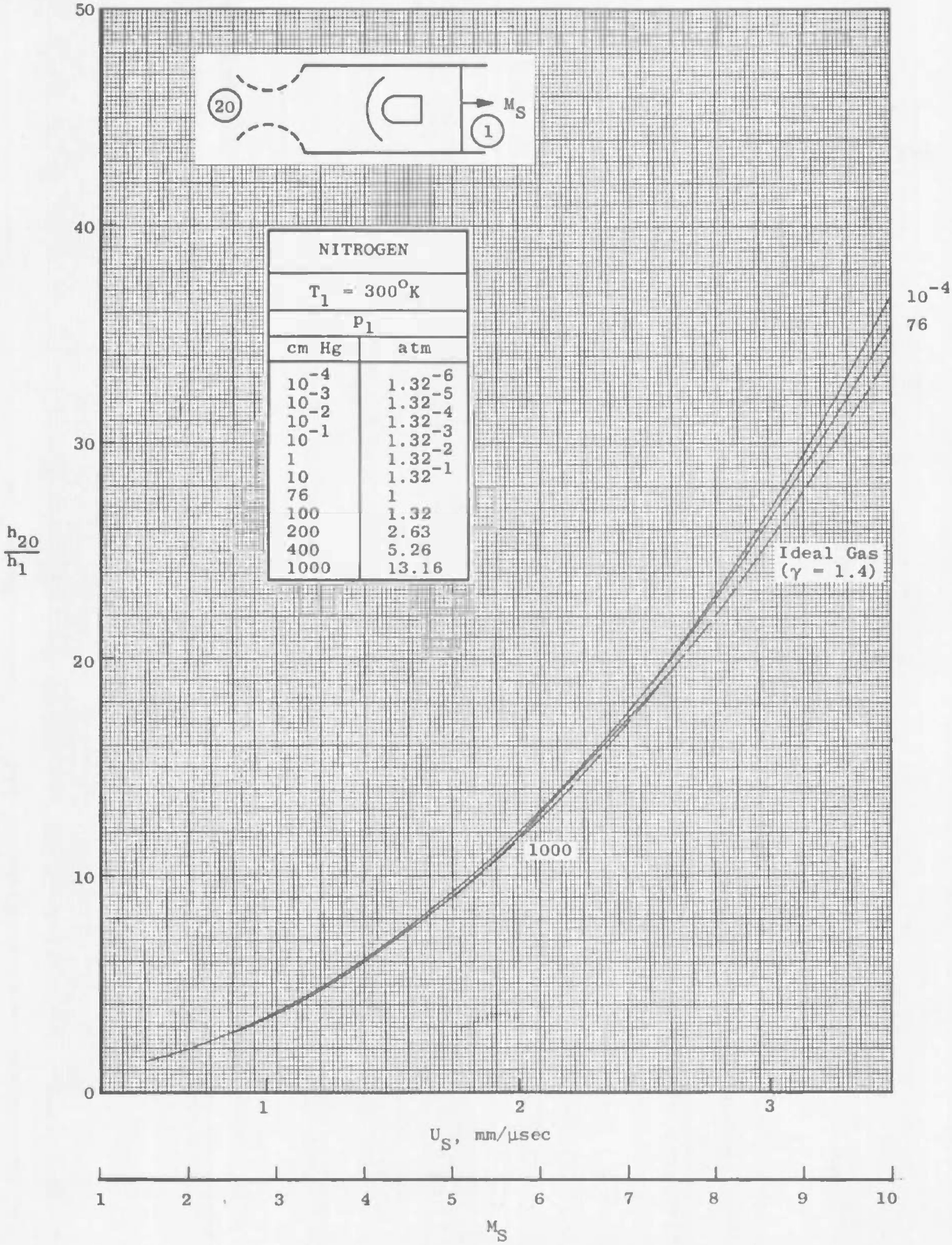
b. ρ_{20}/ρ_1 against Incident Shock Mach Number M_S

Fig. 5 Continued



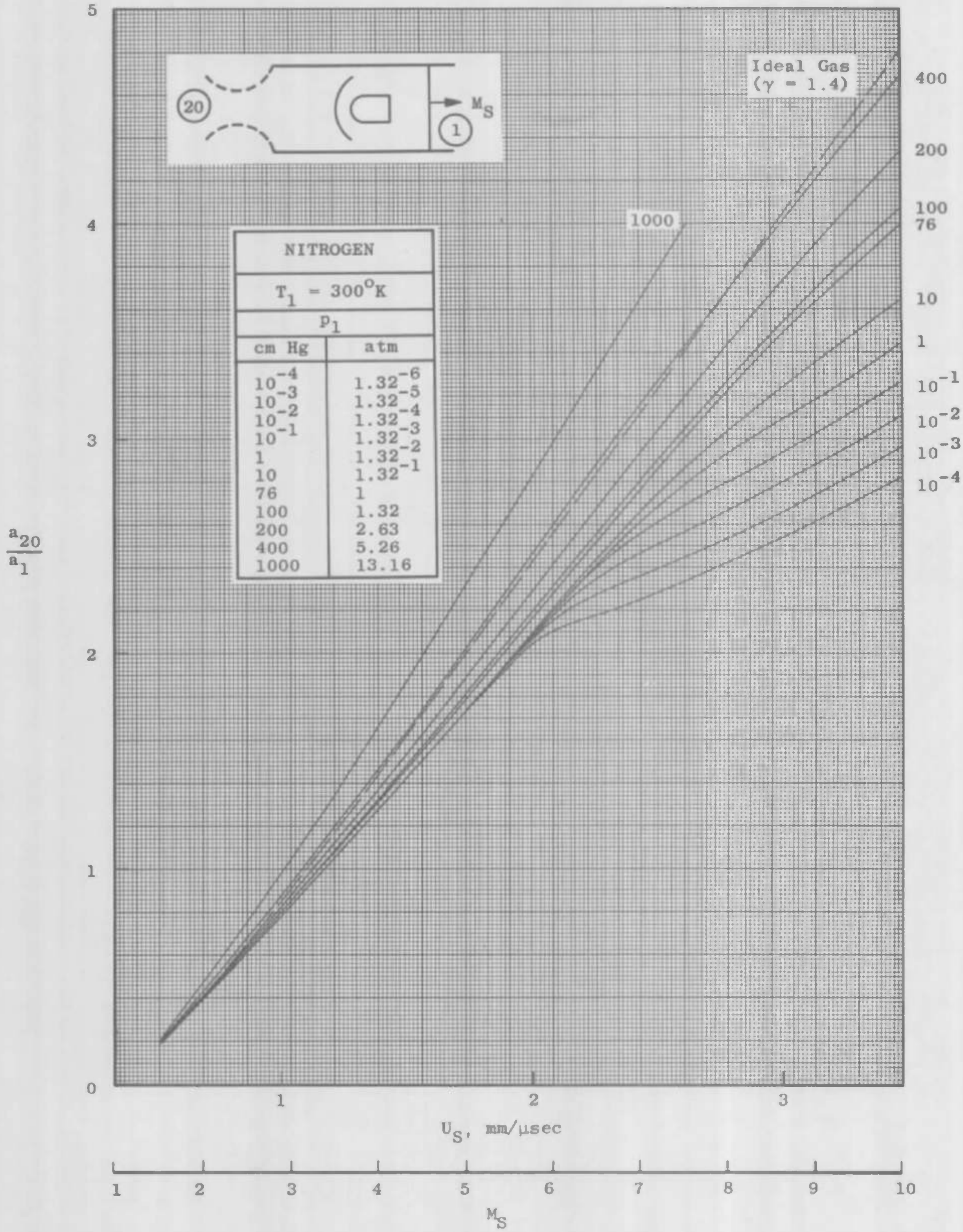
c. T_{20}/T_1 against Incident Shock Mach Number M_S

Fig. 5 Continued



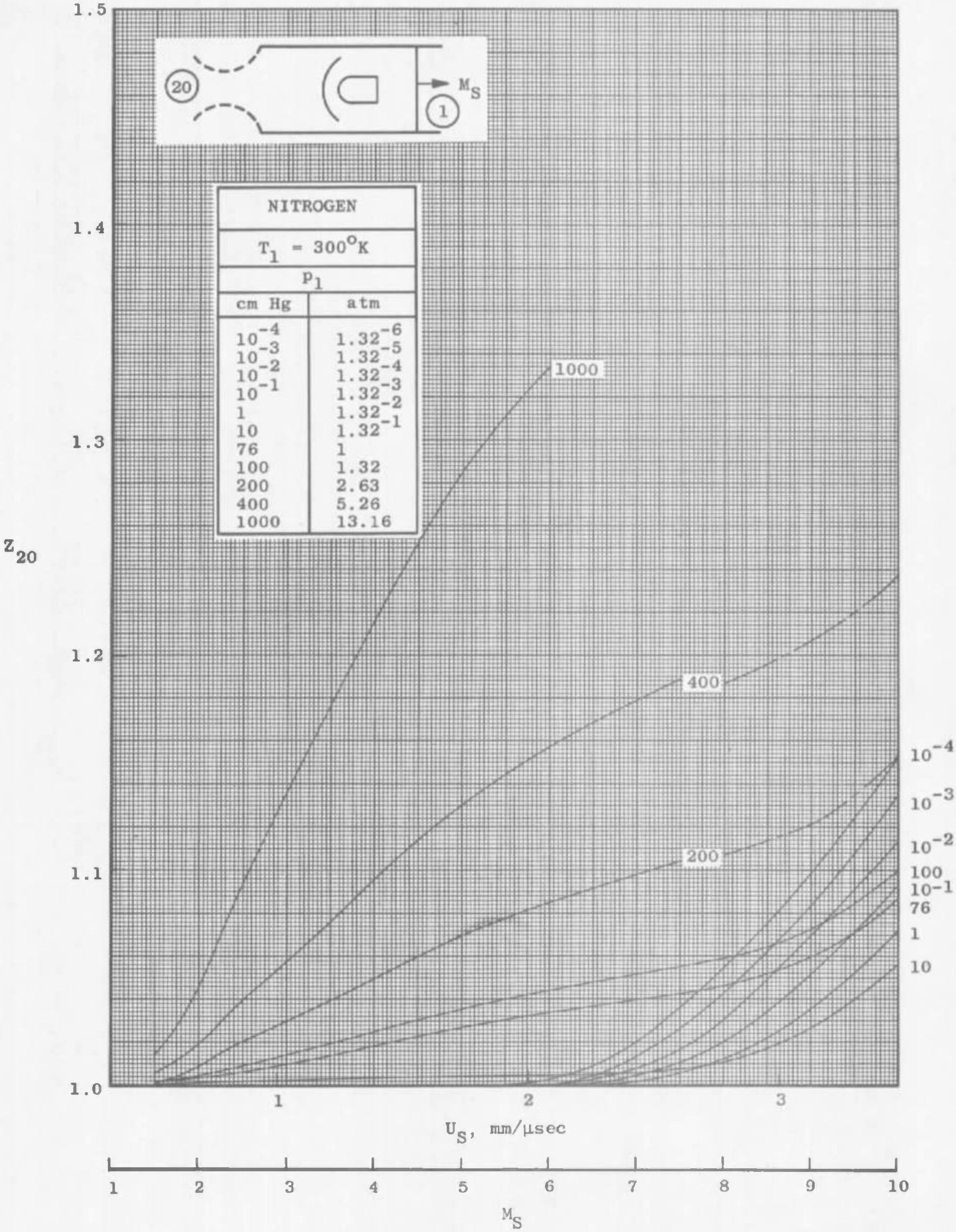
d. h_{20}/h_1 against Incident Shock Mach Number M_S

Fig. 5 Continued



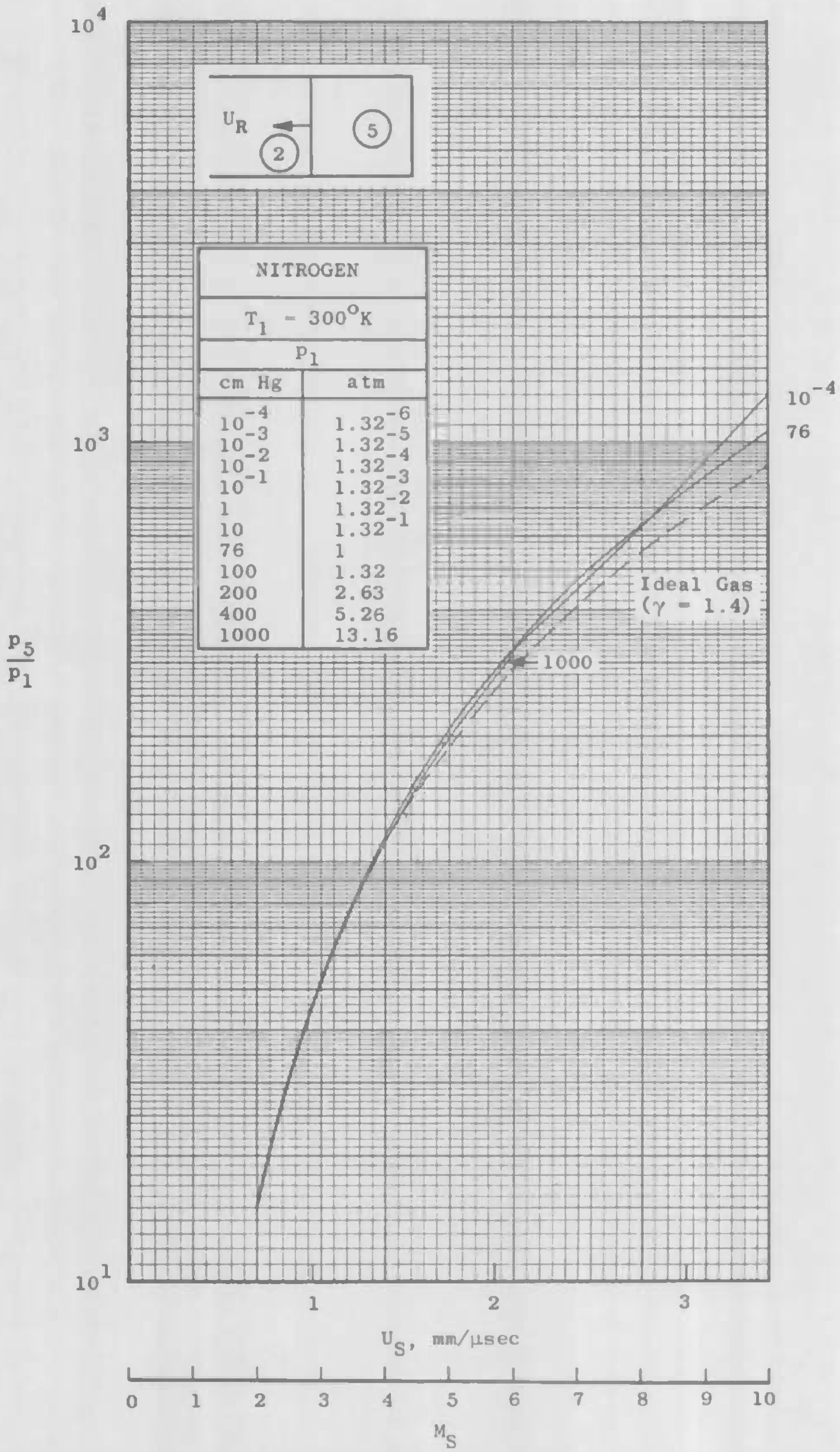
e. a_{20}/a_1 against Incident Shock Mach Number M_S

Fig. 5 Continued



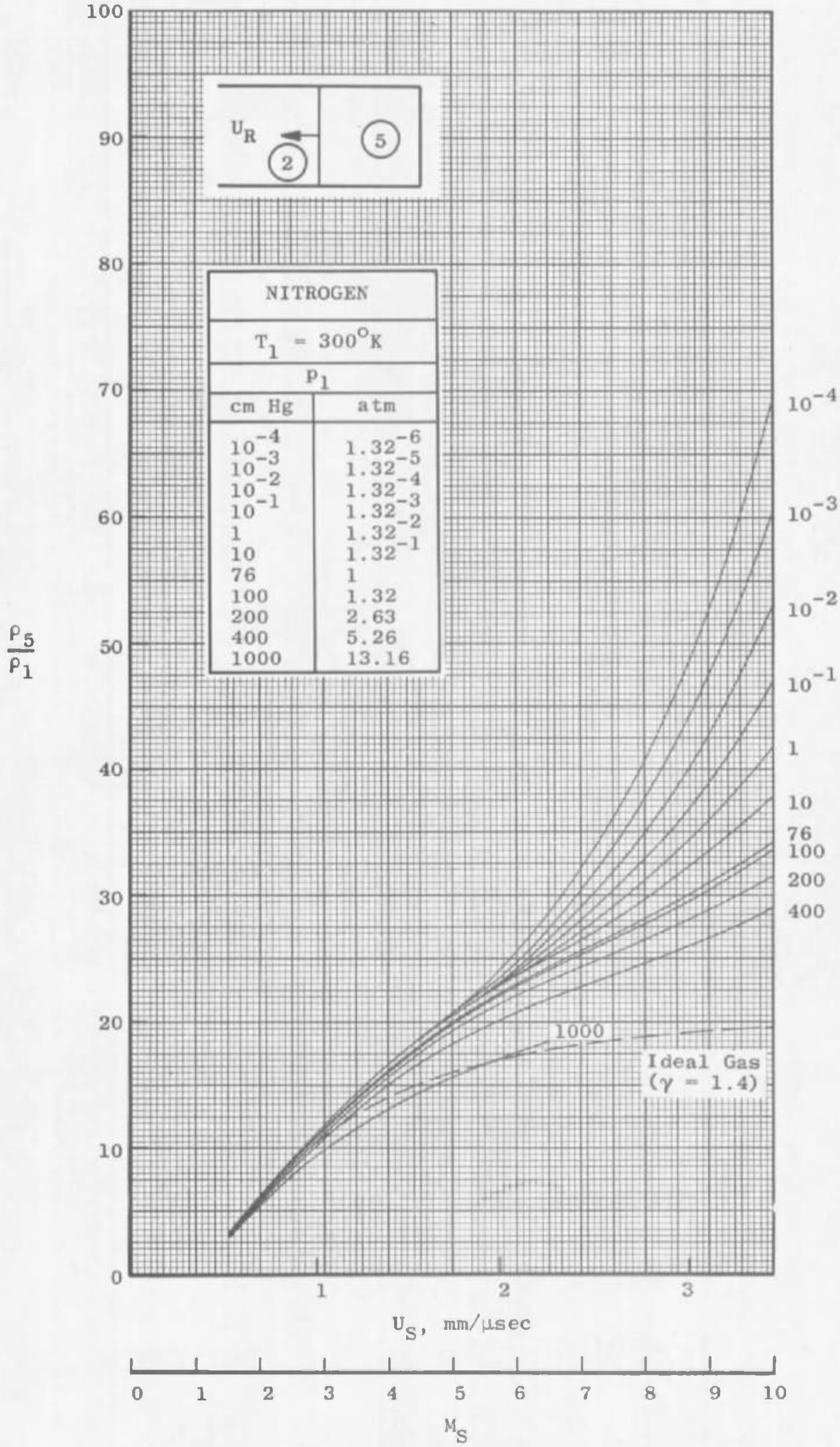
f. Z_{20} against Incident Shock Mach Number M_S

Fig. 5 Concluded



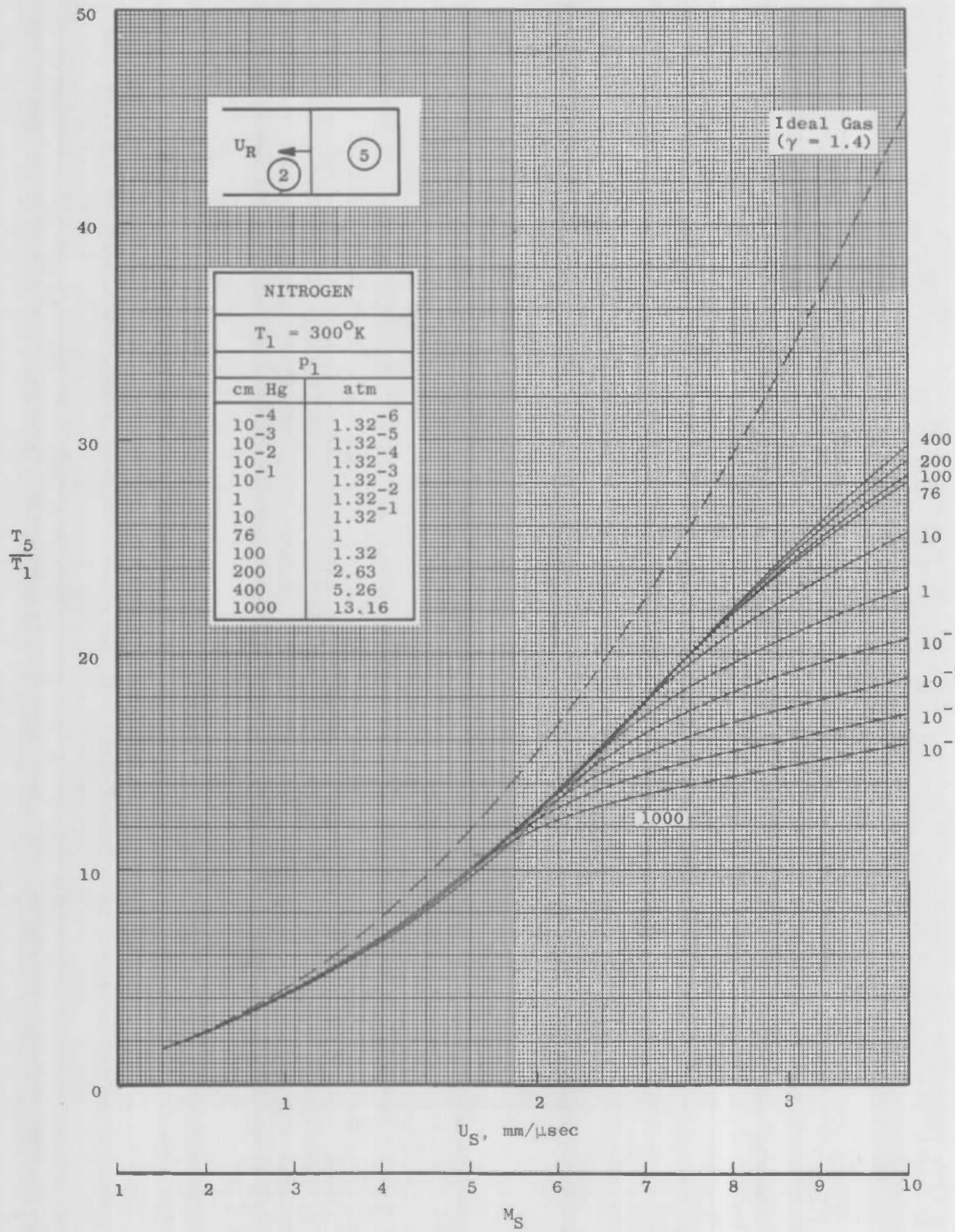
a. p_5/p_1 against Incident Shock Mach Number M_S

Fig. 6 Conditions Behind a Reflected Shock Wave



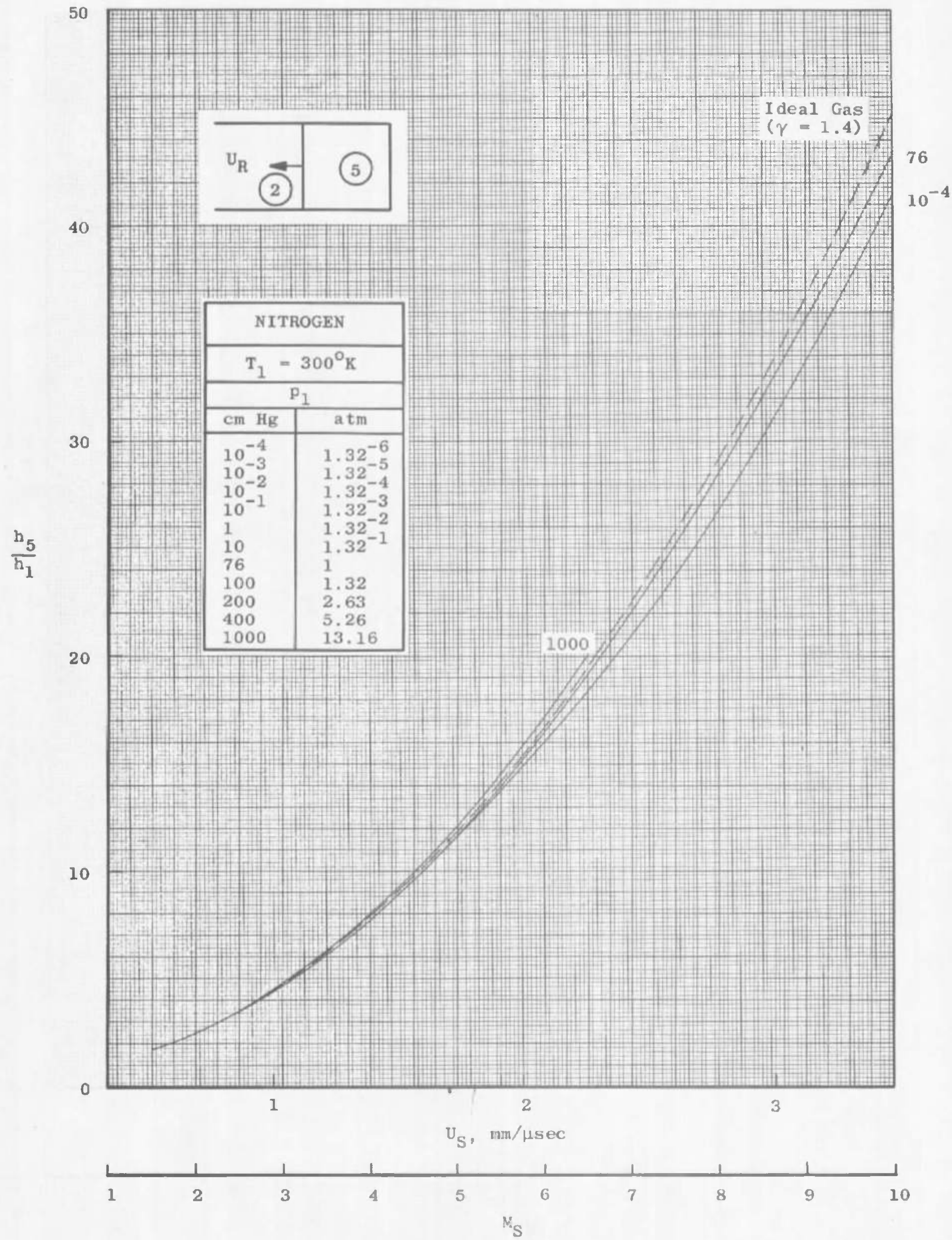
b. ρ_5/ρ_1 against Incident Shock Mach Number M_S

Fig. 6 Continued



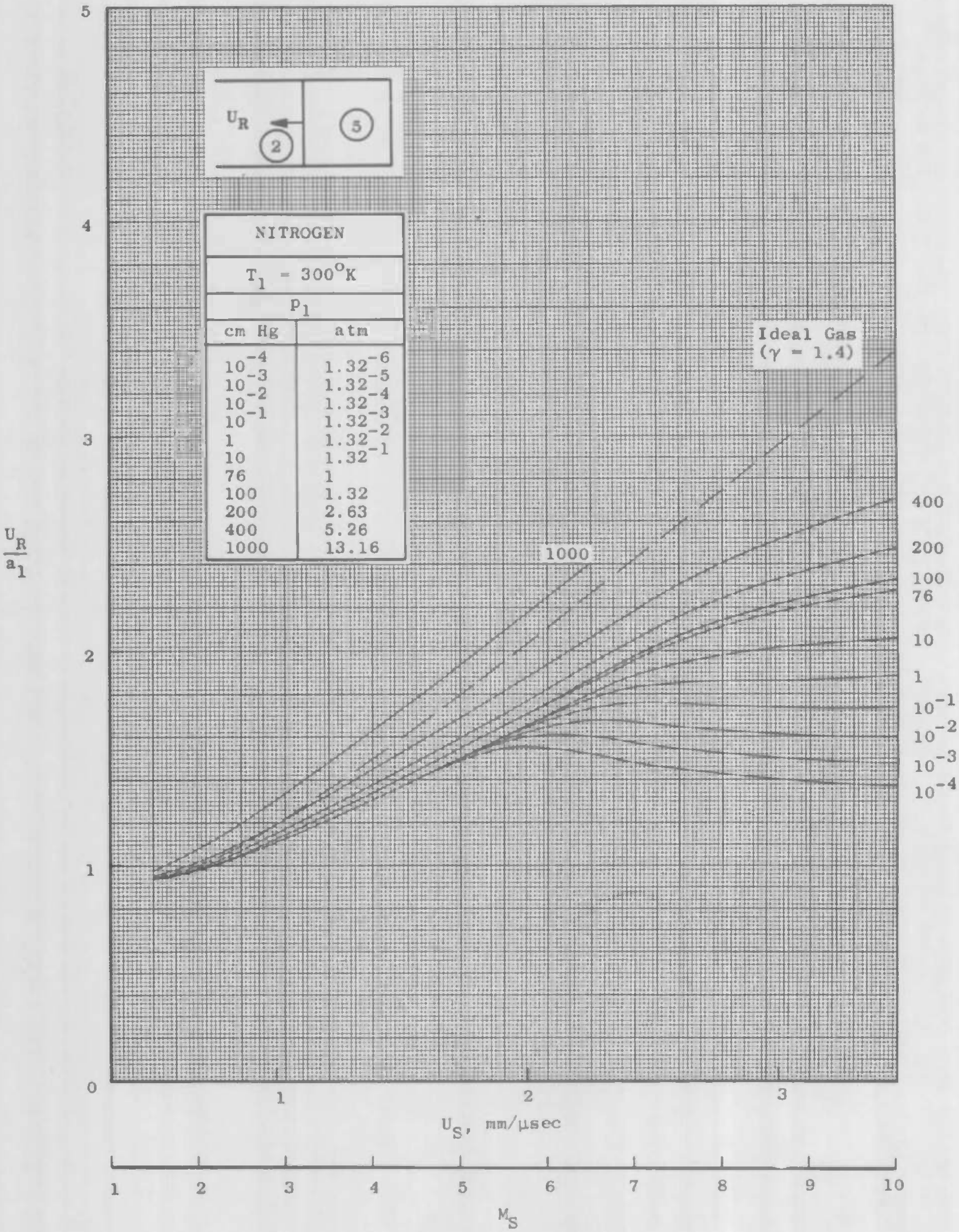
c. T_5/T_1 against Incident Shock Mach Number M_S

Fig. 6 Continued



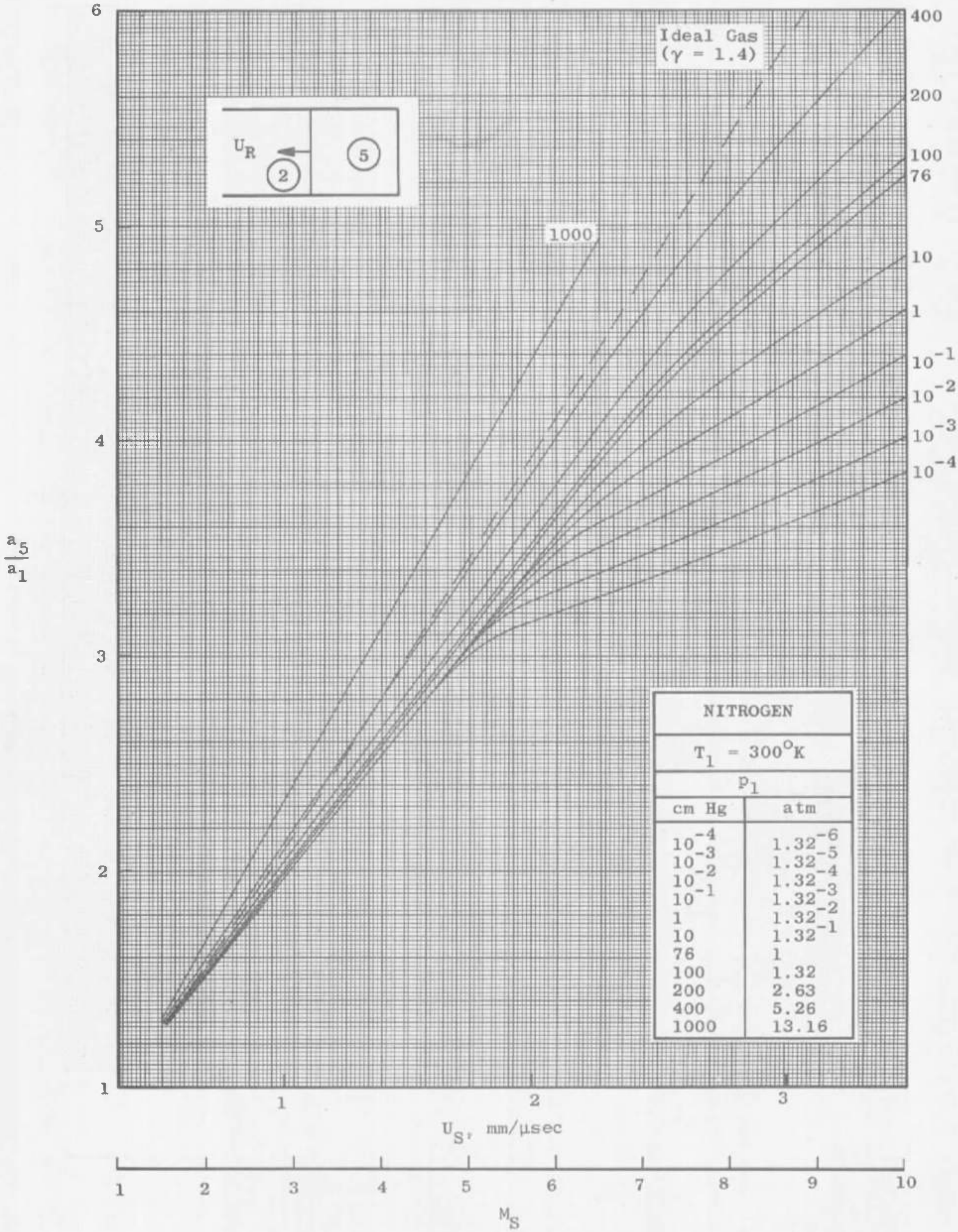
d. h_5/h_1 against Incident Shock Mach Number M_S

Fig. 6 Continued



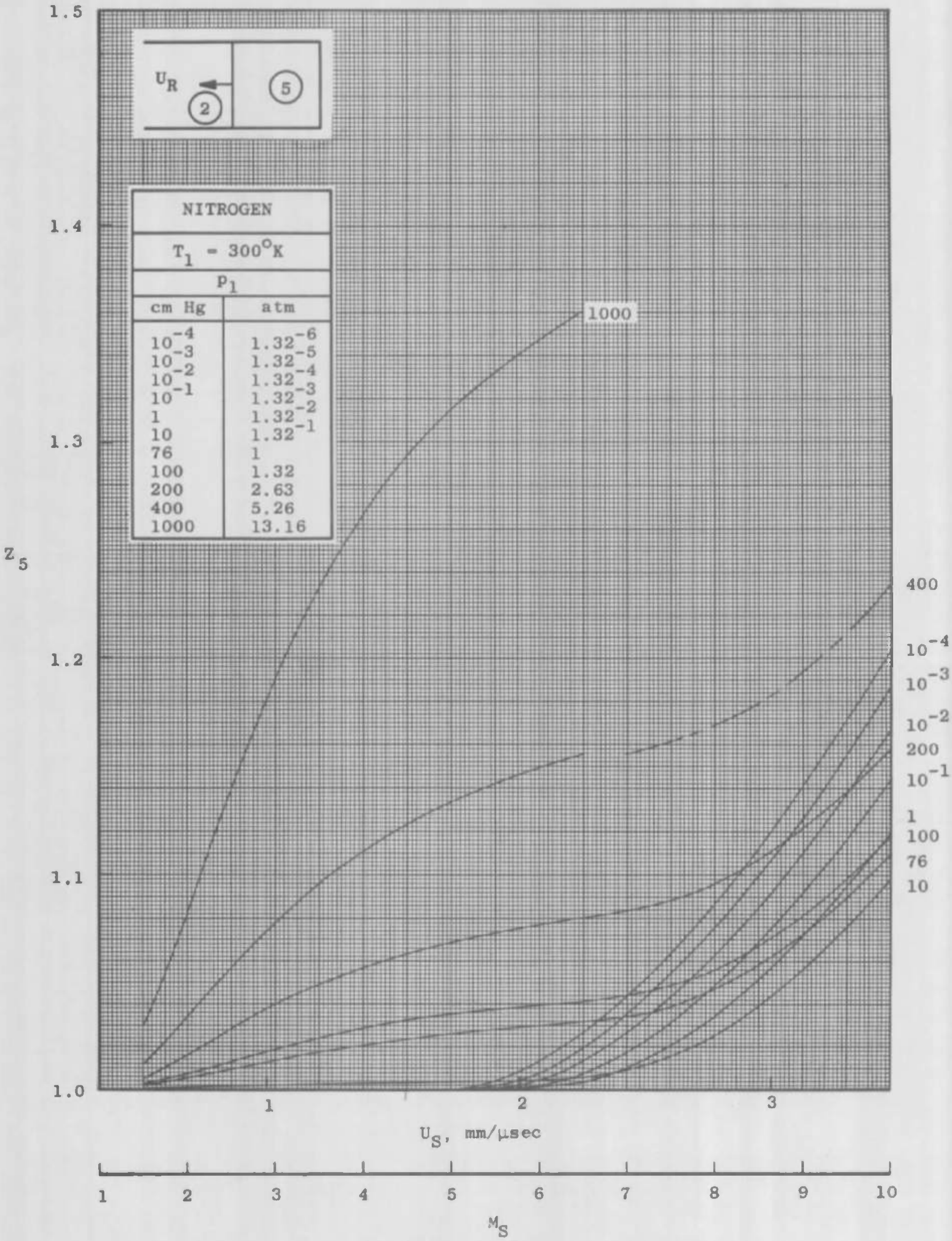
e. U_R/a_1 against Incident Shock Mach Number M_S

Fig. 6 Continued



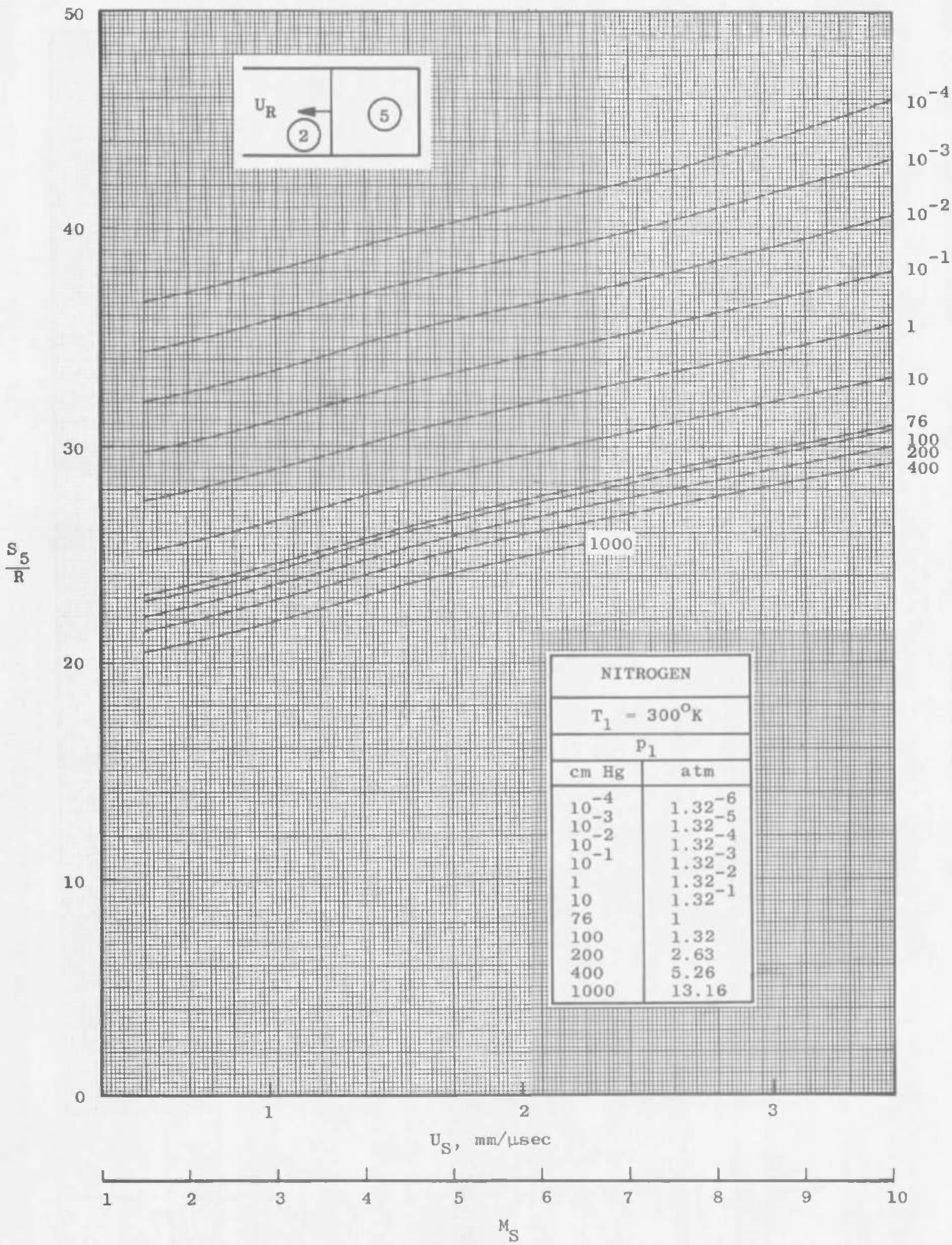
f. a_5/a_1 against Incident Shock Mach Number M_S

Fig. 6 Continued



g. Z_5 against Incident Shock Mach Number M_S

Fig. 6 Continued



h. S_5/R against Incident Shock Mach Number M_S

Fig. 6 Concluded

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 REPORT TITLE

CHARTS OF NORMAL SHOCK WAVE PROPERTIES IN IMPERFECT NITROGEN (SUPPLEMENT: M_S = 1 TO 10

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

N/A

5 AUTHOR(S) (Last name, first name, initial)

Lewis, C. H. and Burgess, E. G., III, ARO, Inc.

6. REPORT DATE	7a TOTAL NO. OF PAGES	7b NO OF REFS
September 1966	57	27

8a CONTRACT OR GRANT NO. AF40(600)-1200 b PROJECT NO 8953 c Program Element 62405334 d Task 895303	9a ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-66-116 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N/A

10 AVAILABILITY/LIMITATION NOTICES Qualified users may obtain copies of this document from DDC. Distribution of this document is unlimited.

11 SUPPLEMENTARY NOTES N/A	12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee

13 ABSTRACT

Gasdynamic properties which include the effects of dissociation and intermolecular forces (van der Waals) are presented for incident and reflected shock waves in equilibrium imperfect nitrogen. Charts are presented for incident shock Mach numbers in the range from 1 to 10 into (ideal) nitrogen at a temperature of 300°K and pressures in the range from 10^{-4} to 10^3 cm Hg. The temperature and density in any region do not exceed, respectively, 15,000°K and 1000 amagats. In addition to the usual incident and reflected shock properties, stagnation conditions upstream and downstream and conditions immediately downstream of a standing shock wave are also presented. At pressures above one atmosphere in the undisturbed gas, the effects of the intermolecular forces on the gasdynamic properties are demonstrated.

DD FORM 1 JAN 64 1473

UNCLASSIFIED

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
shock wave properties						
charts						
nitrogen						
dissociation						
intermolecular forces						
shock waves						
hypersonic flow						
temperature						
density						
gasdynamic properties						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ______________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ______________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ______________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.